



US010959814B2

(12) **United States Patent**
Suttin et al.

(10) **Patent No.:** **US 10,959,814 B2**
(45) **Date of Patent:** **Mar. 30, 2021**

(54) **ROBOTIC DEVICE FOR DENTAL SURGERY**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1048 days.

(21) Appl. No.: **14/932,156**

(22) Filed: **Nov. 4, 2015**

(65) **Prior Publication Data**

US 2016/0157964 A1 Jun. 9, 2016

Related U.S. Application Data

(60) Provisional application No. 62/170,038, filed on Jun. 2, 2015, provisional application No. 62/089,580, filed on Dec. 9, 2014.

(51) **Int. Cl.**

A61B 34/20 (2016.01)

A61B 34/30 (2016.01)

(Continued)

(52) **U.S. Cl.**

CPC **A61C 8/0089** (2013.01); **A61B 34/20** (2016.02); **A61B 34/30** (2016.02); **A61B 34/70** (2016.02);

(Continued)

(58) **Field of Classification Search**

CPC **A61B 34/32**; **A61B 34/20**; **A61B 34/30**; **A61B 17/13211**; **A61B 2034/102**;

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Primary Examiner — Jacqueline T Johanas

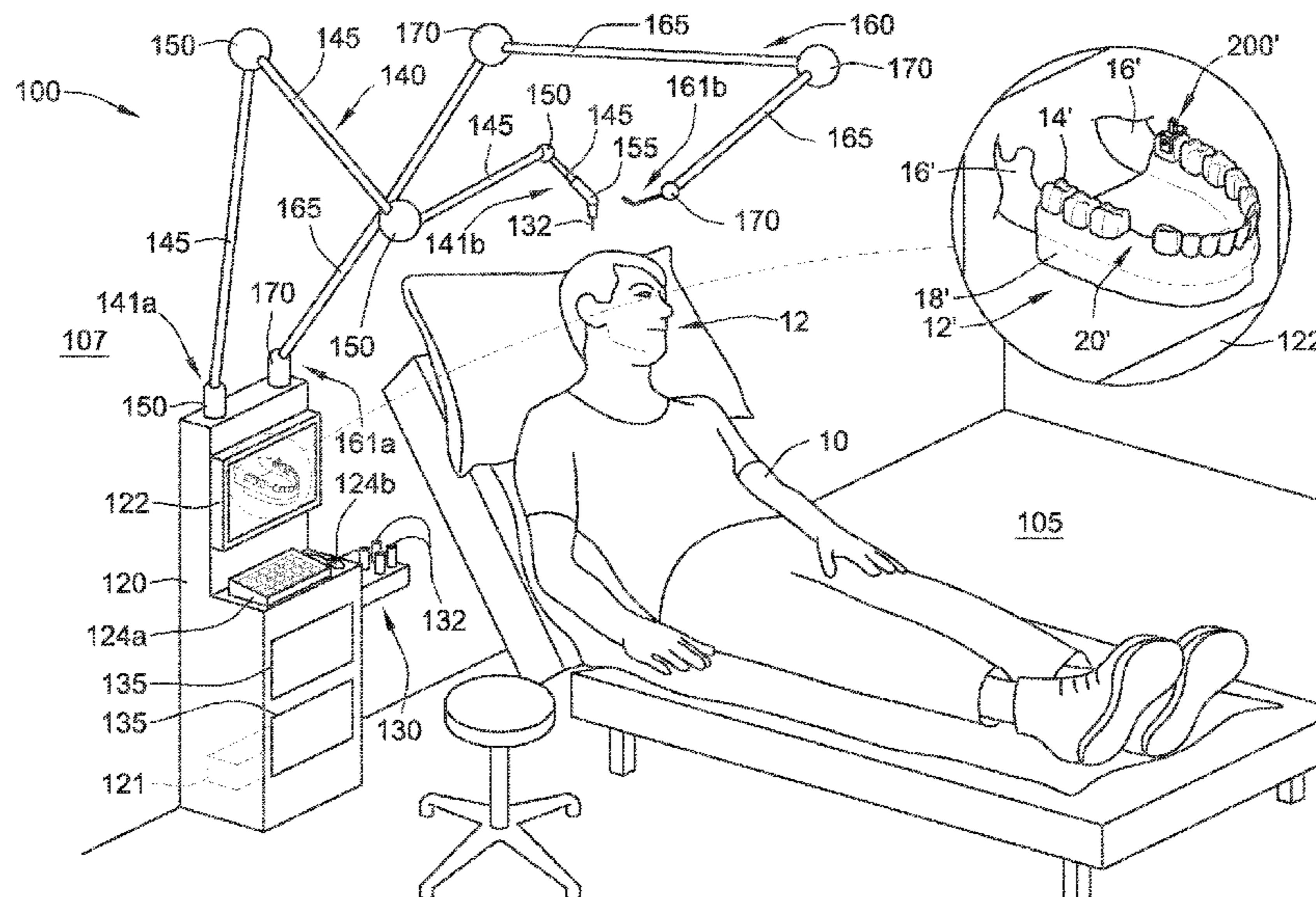
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(57) **ABSTRACT**

A robotic system includes a base, a grounding arm, a working arm, and one or more sensors. The grounding arm extends from the base and is configured to be coupled to a fixed structure within the mouth of the patient for establishing an origin for the robotic system. The working arm extends from the base and is configured to be coupled with one or more tools for use during an installation of a dental implant in the mouth. The one or more sensors are for monitoring positions of the grounding arm and/or the working arm and to generate positional data that is used to create a post-operative virtual three-dimensional model of at least a portion of the mouth of the patient.

16 Claims, 9 Drawing Sheets



- (51) **Int. Cl.**
A61C 1/00 (2006.01)
A61C 1/12 (2006.01)
A61C 3/02 (2006.01)
A61C 3/12 (2006.01)
A61C 8/00 (2006.01)
A61C 9/00 (2006.01)
A61C 1/08 (2006.01)
B25J 9/16 (2006.01)
A61B 34/00 (2016.01)

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- (52) **U.S. Cl.**
 CPC *A61C 1/00* (2013.01); *A61C 1/084* (2013.01); *A61C 1/12* (2013.01); *A61C 3/02* (2013.01); *A61C 3/12* (2013.01); *A61C 9/004* (2013.01); *B25J 9/163* (2013.01); *B25J 9/1682* (2013.01); *Y10S 901/09* (2013.01); *Y10S 901/41* (2013.01)

- (58) **Field of Classification Search**
 CPC ... A61B 2034/105; A61B 34/70; A61C 1/082; A61C 8/0089; A61C 1/00; A61C 1/084; A61C 1/12; A61C 3/02; A61C 3/12; A61C 9/04; B25J 9/163; B25J 9/1682; Y10S 901/09; Y10S 901/41
 USPC 433/72, 76, 79, 73, 74, 75, 77, 78, 80, 433/82, 108, 109
 See application file for complete search history.

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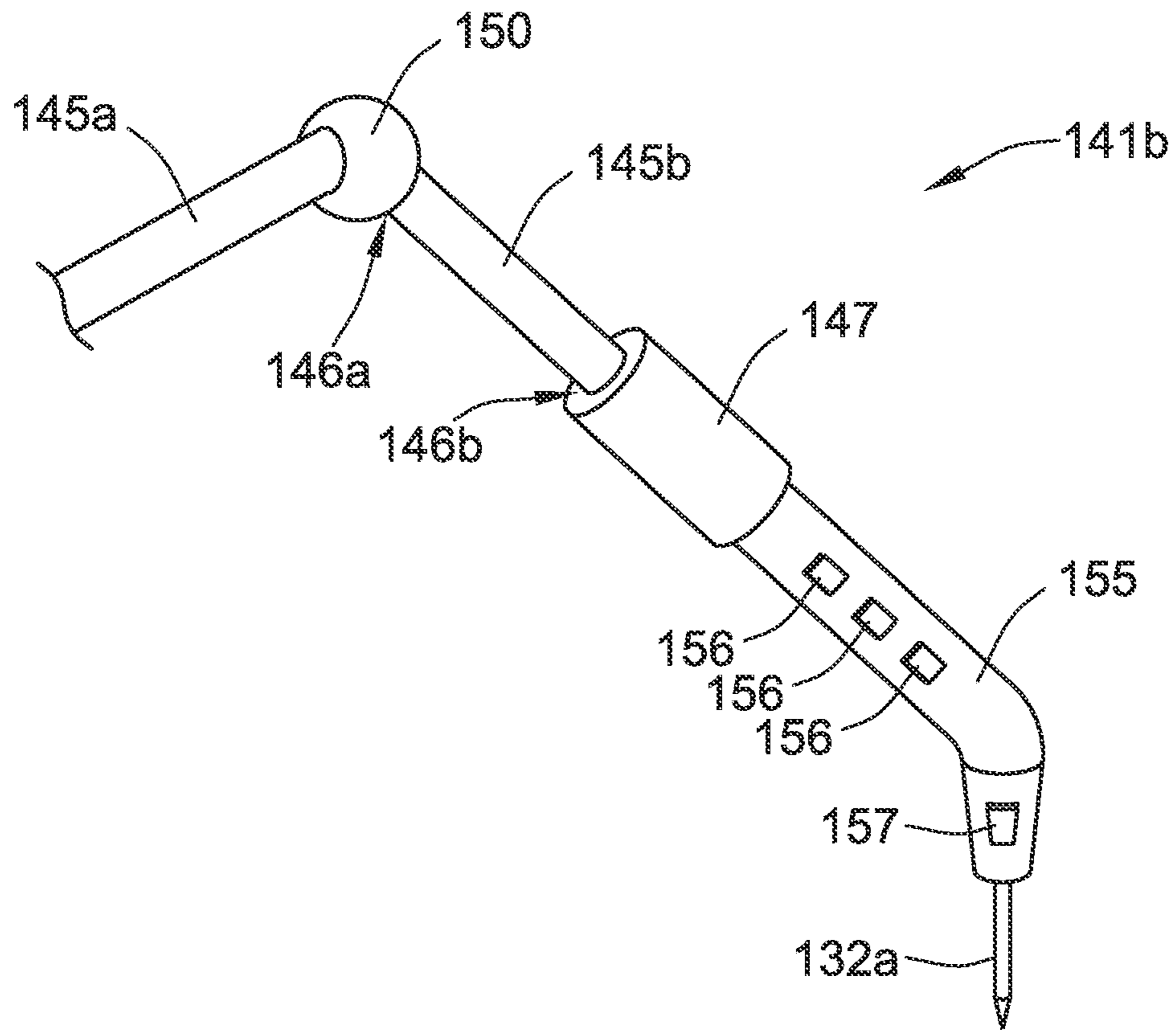


FIG. 2

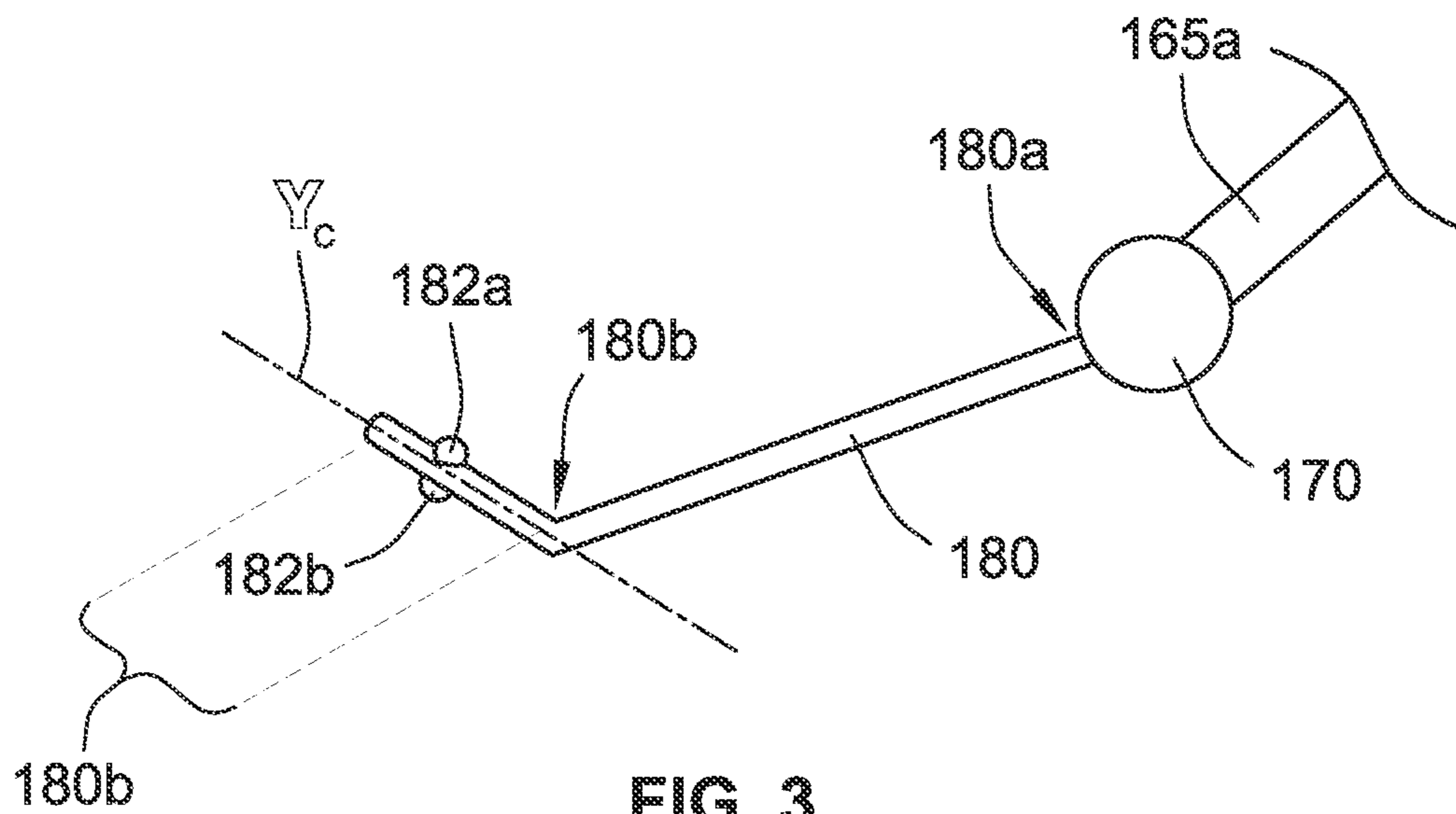


FIG. 3

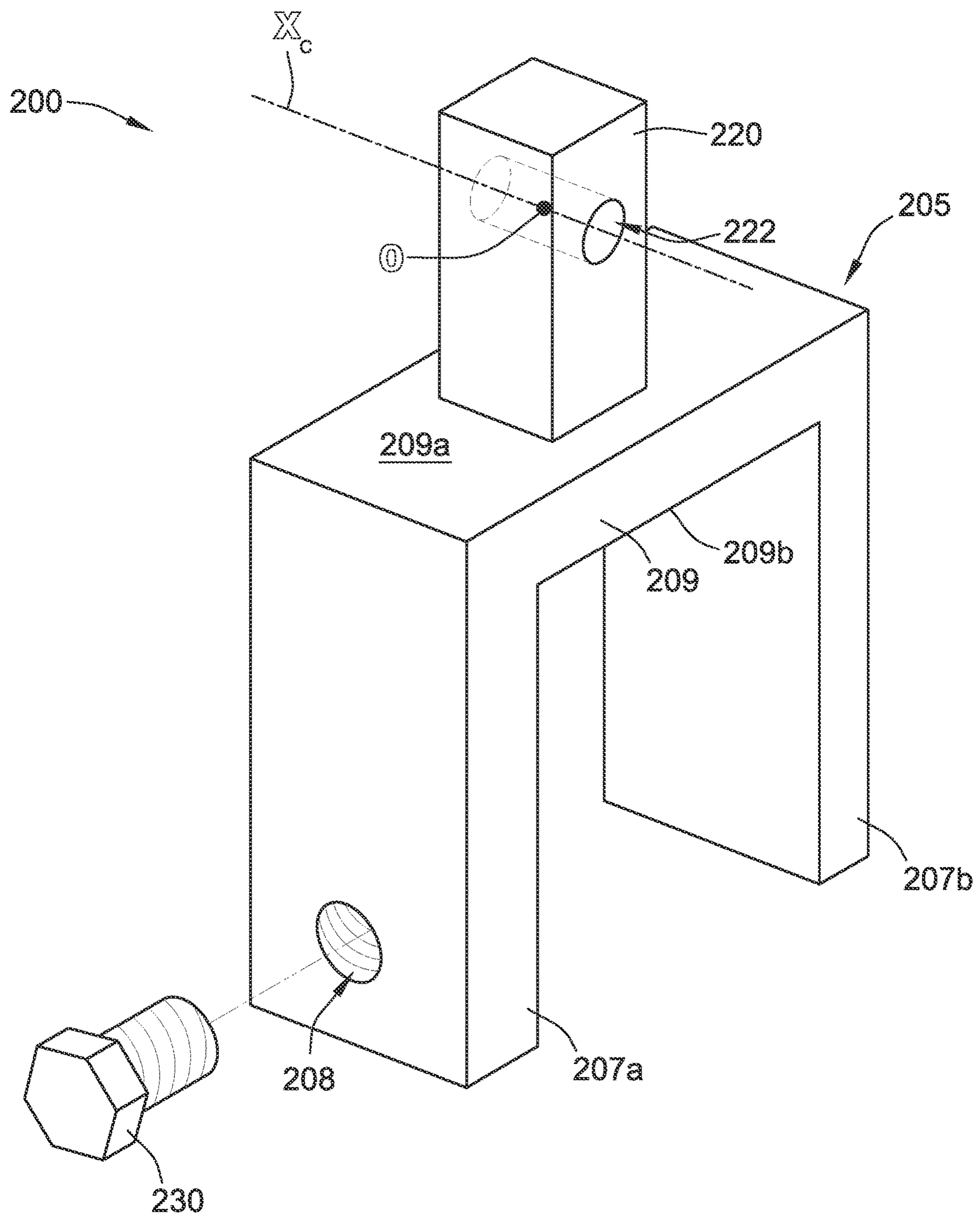
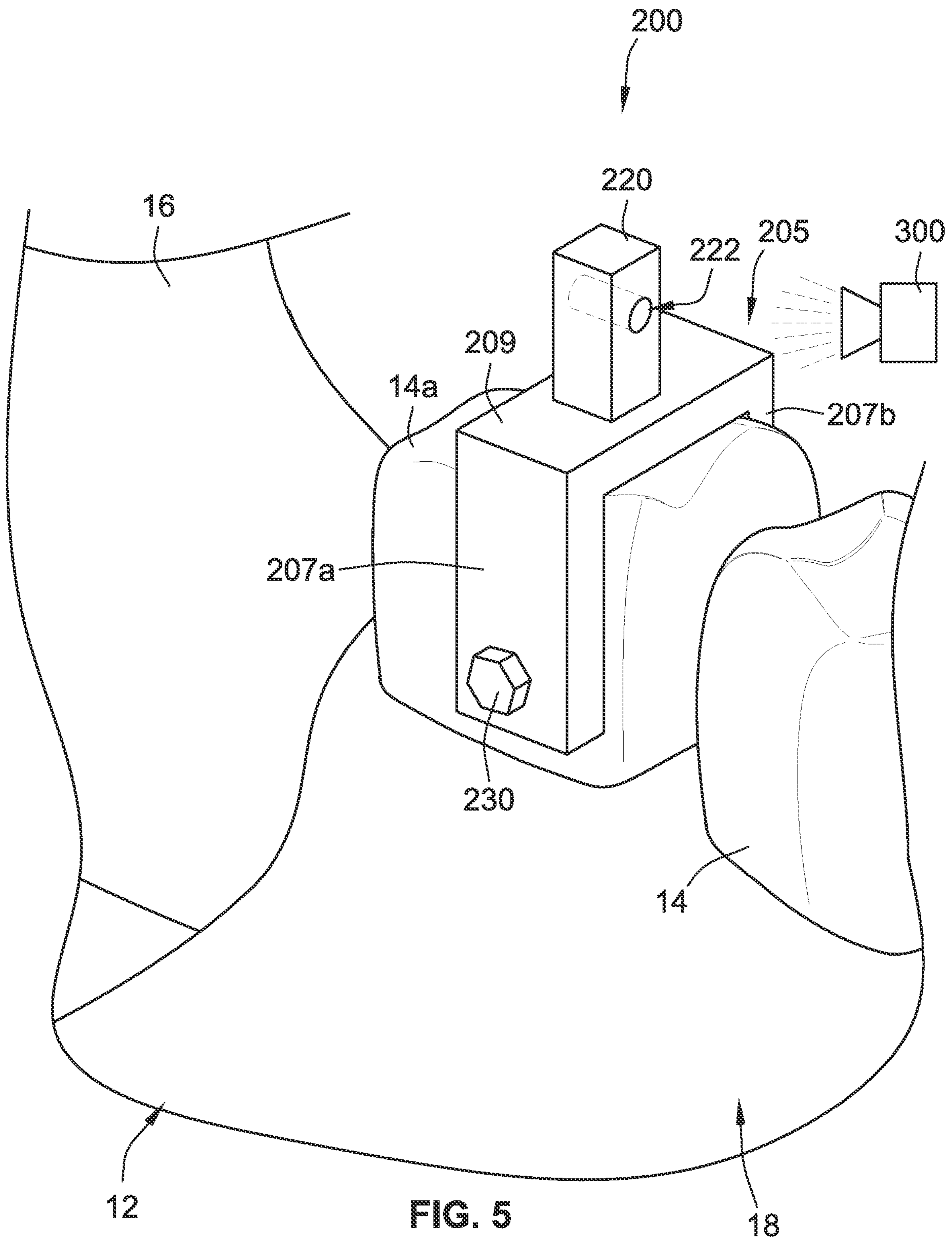
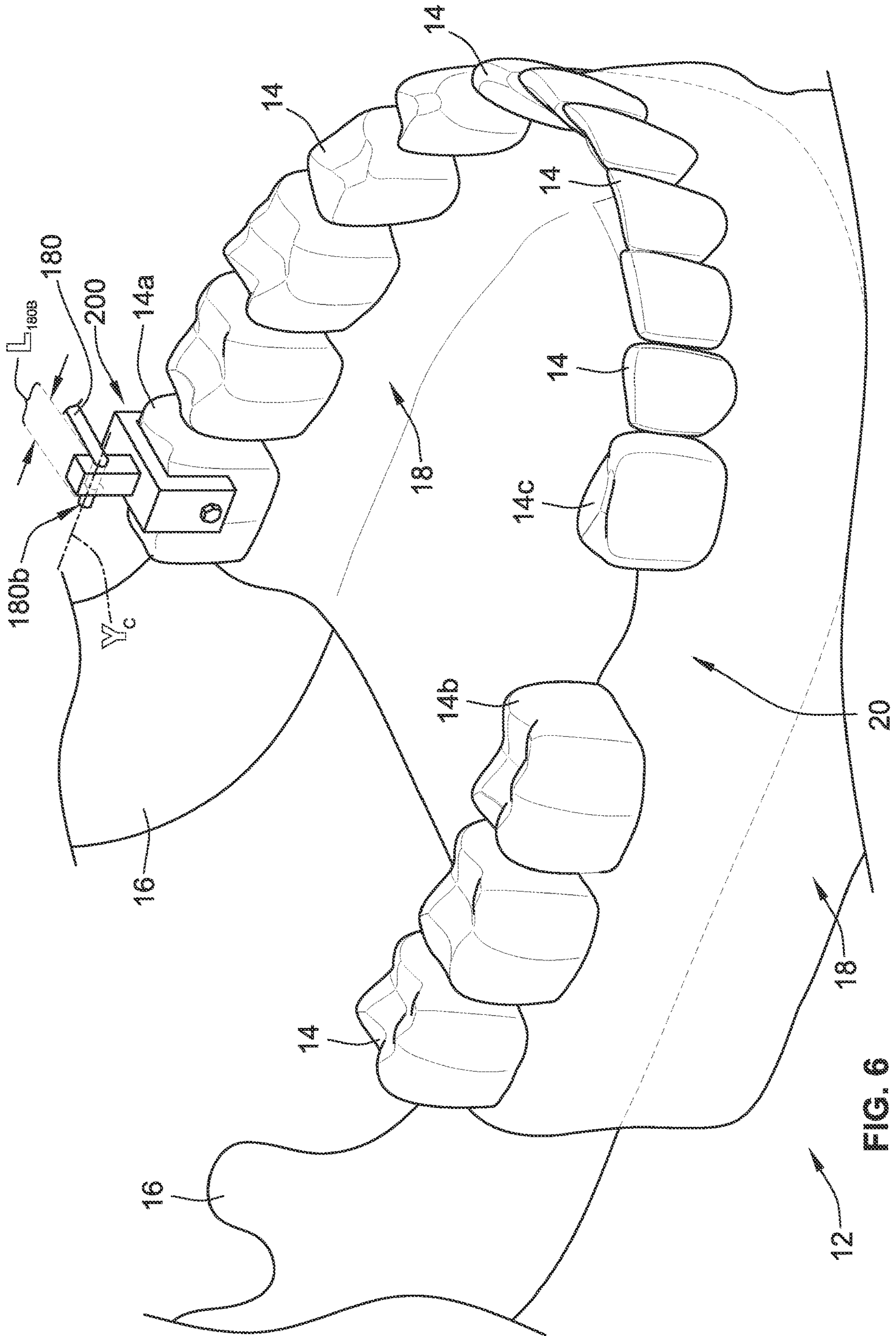


FIG. 4





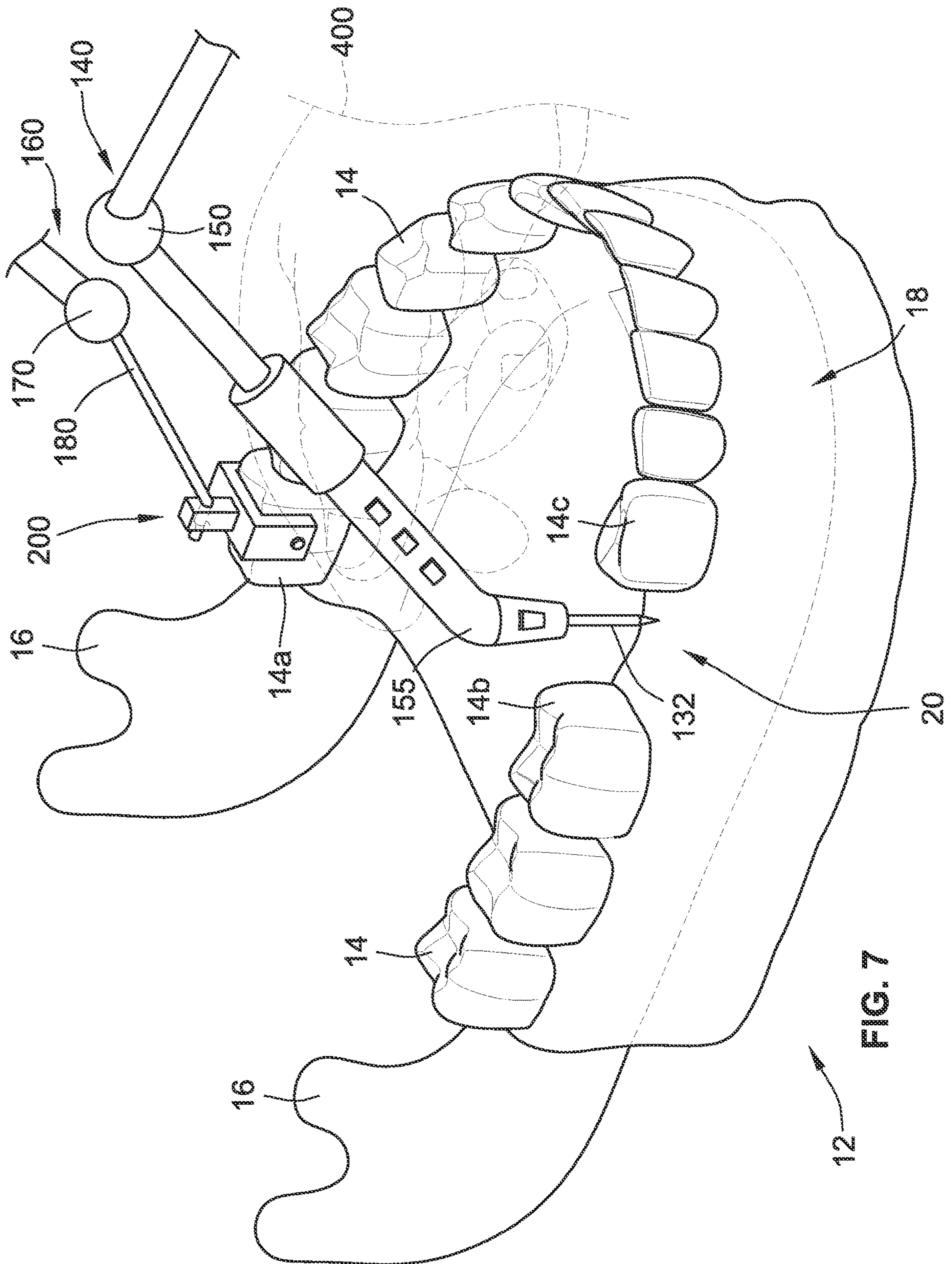


FIG. 7

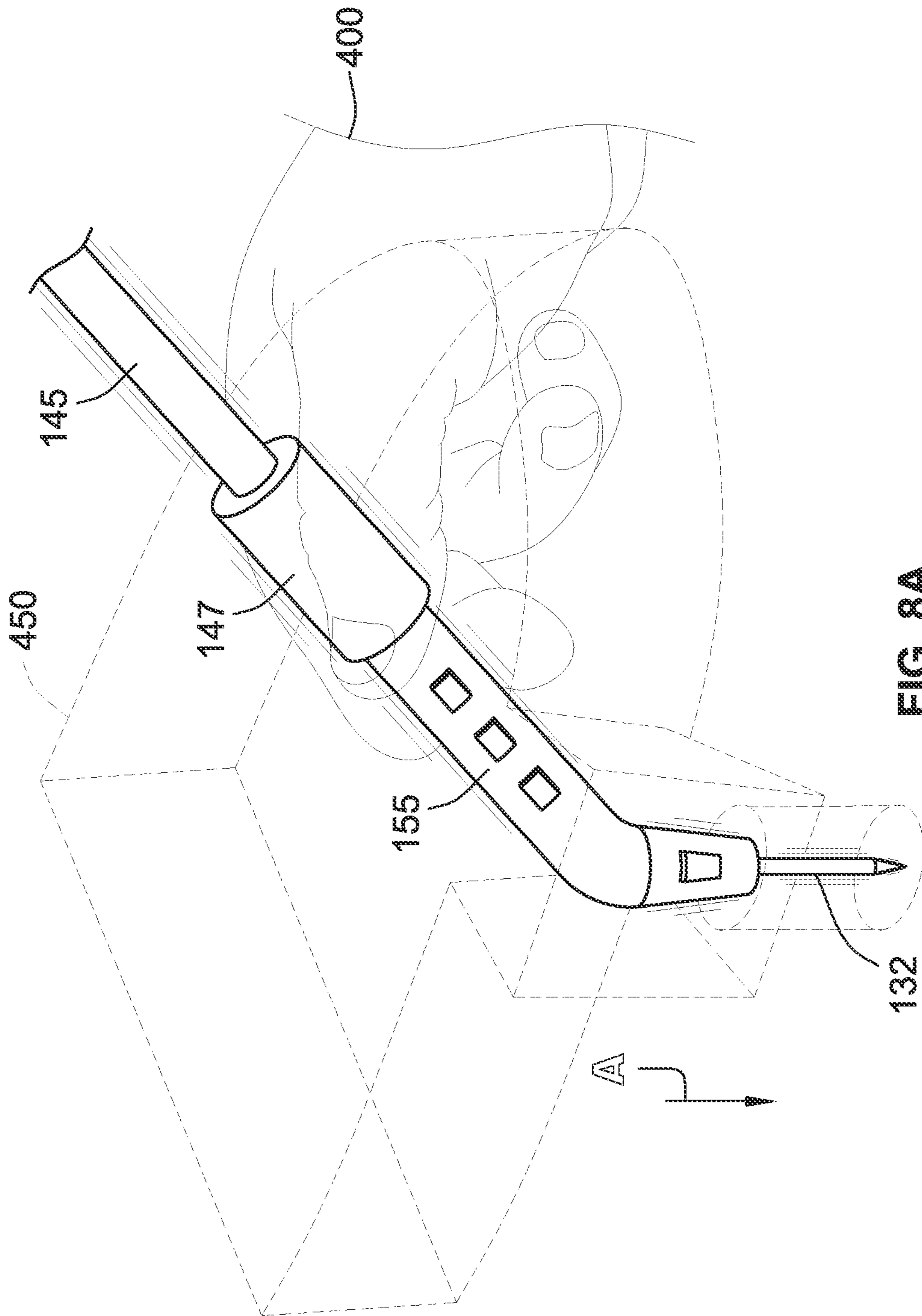


FIG. 8A

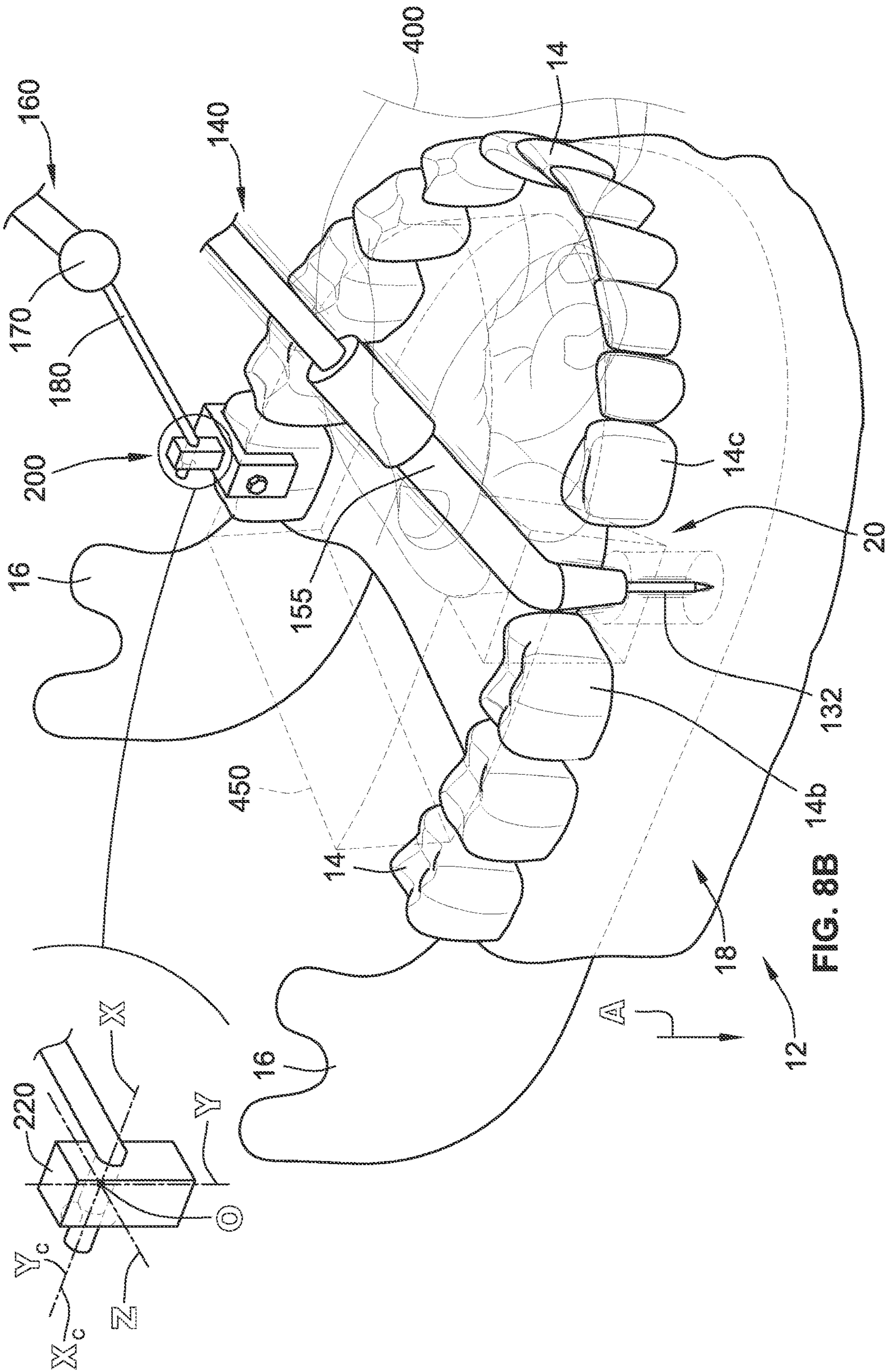
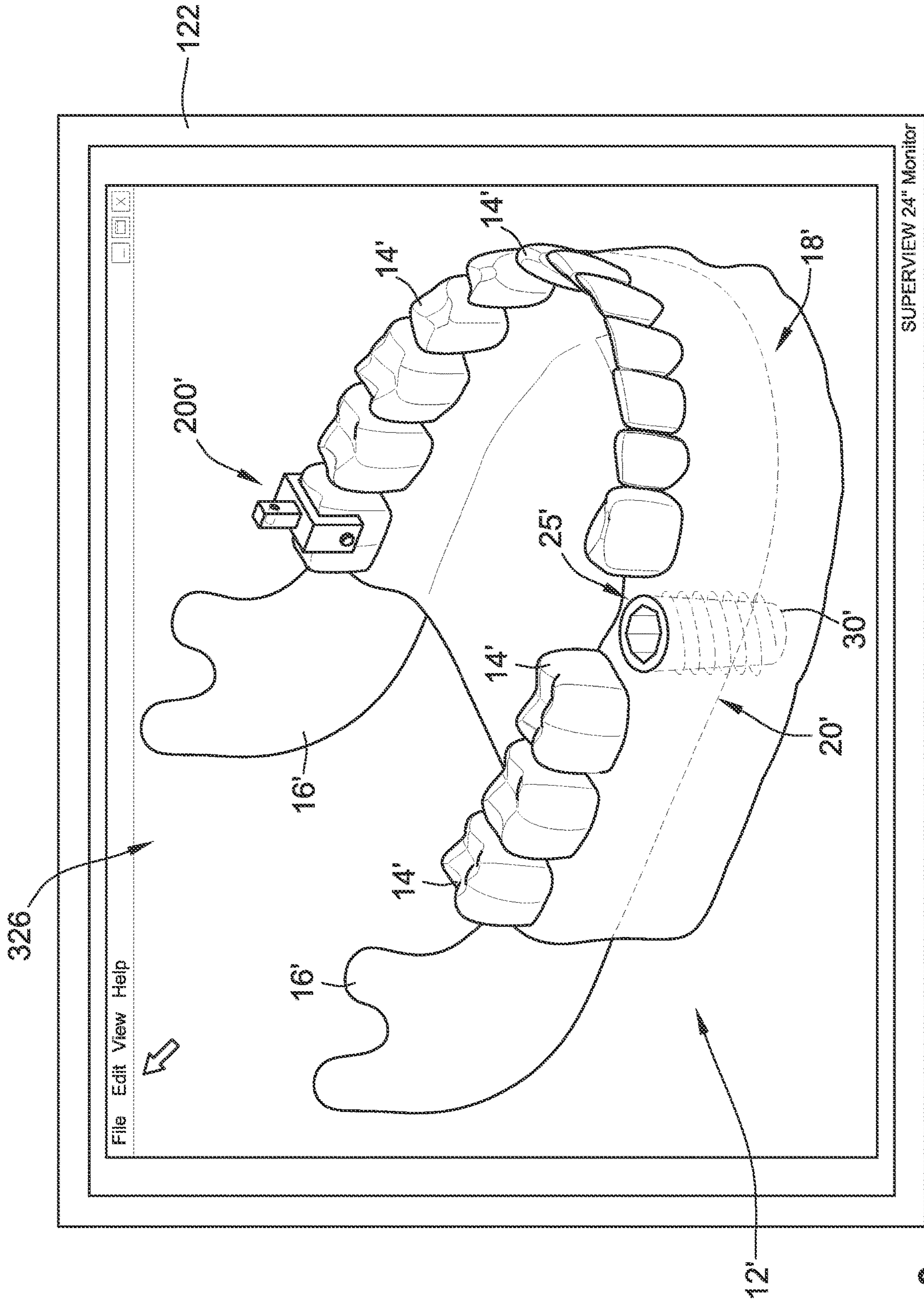


FIG. 8B



SUPERVIEW 24" Monitor

FIG. 9

ROBOTIC DEVICE FOR DENTAL SURGERYCROSS-REFERENCE TO RELATED
APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 62/170,038, filed Jun. 2, 2015, and U.S. Provisional Application No. 62/089,580, filed Dec. 9, 2014, each of which is hereby incorporated by reference herein in its entirety.

FIELD OF THE INVENTION

The present disclosure relates generally to robotic systems and methods of using the same. More particularly, the present disclosure relates to using a robotic system to (i) automatically perform a variety of dental procedures and/or (ii) monitor a manually performed dental procedure, thereby generating positional data of the robotic system that is usable in creating a modified three-dimensional model for use in developing a final and/or temporary dental prosthesis (e.g., crown, abutment, etc.).

BACKGROUND OF THE INVENTION

The dental restoration of a partially or wholly edentulous patient with artificial dentition typically begins with an incision being made through the patient's gingiva to expose the underlying bone. An artificial tooth root, in the form of a dental implant, is placed in the jawbone for osseointegration. The dental implant generally includes a threaded bore configured to receive a retaining screw for holding mating components (e.g., temporary tooth prosthesis, permanent abutment, permanent crown, etc.) thereon. After the dental implant is placed, the gum tissue overlying the dental implant is sutured and heals as the osseointegration process continues.

Once the osseointegration process is complete, the gingival tissue is re-opened to expose an end of the dental implant. A healing component or healing abutment is fastened to the exposed end of the dental implant to allow the gingival tissue to heal therearound. It should be noted that the healing abutment can be placed on the dental implant immediately after the implant has been installed and before osseointegration, thereby, for some situations, combining the osseointegration step and gingival healing step into a one-step process.

At some point thereafter, designing of permanent components to be attached to the dental implant begins. The permanent components are typically referred to as a prosthetic tooth (e.g., permanent abutment plus a permanent crown attached thereto in the shape of a tooth). The design and manufacture of these permanent components requires highly skilled individuals working with models of the mouth of the patient to design components that will look good and function properly (e.g., fit between the adjacent teeth, etc.).

While the models used to design the permanent components are typically physical models made from impressions of the mouth of the patient, in recent years, the designing of the permanent components to be attached to the manually installed dental implant has involved the use of computers and virtual three-dimensional models of the mouth of the patient. In order to accurately design permanent components that mate with the manually installed dental implant in a planned manner (i.e., with a planned rotational orientation and a planned vertical dimension of occlusion), precise details about the location and rotational orientation of the

manually installed dental implant must be known and incorporated in to the virtual three-dimensional model.

In order to obtain this information, prior systems have used scanning abutments that replace the healing abutment for a short period of time and require an intraoral scan of the mouth of the patient to obtain the required data to create the virtual three-dimensional model. The replacing of the healing abutment with the scanning abutment, even for a short period of time, has disadvantages, such as, added discomfort to the patient having to have additional procedures performed, disruption to the gingival healing process, etc.

However, some other prior systems use coded healing abutments that have scannable features (e.g., markers) thereon that when scanned and interpreted, provide the necessary information about the location and orientation of the underlying dental implant to create the virtual three-dimensional model without the need to remove the healing abutment and place a separate scanning abutment in the mouth of the patient. While these systems do not require the removal of the healing abutment to create the virtual three-dimensional model, they still do require the intraoral scanning step, which requires expensive intraoral scanning equipment. The present disclosure is directed to solving these and other needs.

SUMMARY OF THE INVENTION

According to some implementations, a robotic system for use during a dental surgical procedure including installation of a dental implant in a mouth of a patient includes a base; a grounding arm having a first end and a second end, the first end of the grounding arm being coupled to the base, the second end of the grounding arm being configured to be coupled to a fixed structure within the mouth of the patient for establishing an origin for the robotic system relative to the mouth of the patient, the second end of the grounding arm having at least six degrees of freedom relative to the base; a working arm having a first end and a second end, the first end of the working arm extending from the base, the second end of the working arm being configured to be coupled with one or more tools for use during the dental surgical procedure, a portion of the working arm having at least six degrees of freedom relative to the base and being moveable to (i) form an opening in bone within the mouth of the patient and (ii) install the dental implant in the formed opening; and one or more sensors to monitor positions of the grounding arm and the working arm, the one or more sensors generating positional data that is used to create a post-operative virtual three-dimensional implant level model of at least a portion of the mouth of the patient.

According to some implementations, a robotic system for use during installation of a dental implant in a mouth of a patient includes a base; a grounding arm extending from the base and being configured to be coupled to a fixed structure within the mouth of the patient for establishing an origin for the robotic system relative to the mouth of the patient; a working arm extending from the base and being configured to be coupled with one or more tools for use during the installation of the dental implant, at least a portion of the working arm being movable to install the dental implant in the mouth of the patient; and one or more sensors to monitor positions of the grounding arm and the working arm, the one or more sensors generating positional data that is used to create a virtual model of at least a portion of the mouth of the patient.

According to some implementations, a method of creating a post-operative virtual model of at least a portion of a

mouth of a patient, where the mouth includes a dental implant installed using a robotic system during a dental surgical procedure, includes attaching a rigid grounding member to a fixed position within the mouth of the patient; obtaining a pre-operative virtual model of the mouth of the patient with the rigid grounding member therein; coupling a grounding arm of the robotic system to the rigid grounding member in the mouth of the patient, thereby establishing an origin for the mouth of the patient; moving, as part of the dental surgical procedure, at least a portion of a working arm of the robotic system coupled to a dental-implant-driving tool to install the dental implant in the mouth of the patient; monitoring, during the dental surgical procedure, a position of the grounding arm and the working arm to generate positional data related to the location of the dental-implant-driving tool relative to the established origin; and creating the post-operative virtual model of the at least a portion of the mouth of the patient based on the obtained pre-operative virtual model and the generated positional data.

According to some implementations, a method of automatically shaving alveolar bone in a mouth of a patient using a robotic system includes attaching a rigid grounding member to a fixed position within the mouth of the patient; obtaining a pre-shaved virtual model of the mouth of the patient with the rigid grounding member therein; coupling a grounding arm of the robotic system to the rigid grounding member in the mouth of the patient, thereby establishing an origin for the mouth of the patient; developing a plan for automatically moving a bone-cutting tool relative to the established origin to shave a portion of the alveolar bone in the mouth of the patient; attaching the bone-cutting tool to a working arm of the robotic system; and executing the developed plan by automatically moving the bone-cutting tool via the working arm of the robotic system, thereby shaving the alveolar bone in the mouth of the patient according to the developed plan such that an exposed ridge of the alveolar bone in the mouth of the patient is sufficiently widened for drilling and receiving a dental implant therein.

According to some implementations, a method of installing a dental implant in a mouth of a patient using a robotic system includes developing a plan for installing the dental implant in the mouth of the patient, the developed plan including (i) a first sub-plan for shaving an exposed portion of bone in the mouth with a first tool, thereby creating a sufficiently widened portion of the bone for receiving the dental implant therein, (ii) a second sub-plan for forming an opening in the sufficiently widened portion of the bone to receive the dental implant with a second tool, and (iii) a third sub-plan for installing the dental implant within the opening with a third tool; establishing an origin for the mouth of the patient by coupling a grounding arm of the robotic system to a rigid grounding member in the mouth of the patient; and executing the plan by: (A) coupling the first tool to a working arm of the robotic system and shaving the exposed portion of the bone in the mouth of the patient by moving at least a portion of the working arm according to the first sub-plan; (B) coupling the second tool to the working arm of the robotic system and forming the opening in the bone in the mouth of the patient by moving the at least a portion of the working arm according to the second sub-plan; and (C) coupling the third tool and the dental implant to the working arm of the robotic system and installing the dental implant into the opening in the bone in the mouth of the patient by moving the at least a portion of the working arm according to the third sub-plan.

According to some implementations, a method of shaving alveolar bone in a mouth of a patient using a robotic system

includes establishing an origin for the mouth of the patient by coupling a grounding arm of the robotic system to a rigid grounding member in the mouth of the patient; determining an invisible boundary wall to be established around a pre-determined location in the mouth of the patient; coupling a bone-cutting tool to a working arm of the robotic system; moving at least a portion of the working arm of the robotic system to shave the alveolar bone in the mouth of the patient; during the moving, automatically enforcing the determined invisible boundary wall by preventing the working arm of the robotic system from being moved in a manner that would cause the bone-cutting tool to be moved past the determined invisible boundary wall; and monitoring, during the moving, a position of the grounding arm and the working arm to generate positional data related to the location of the bone-cutting tool relative to the established origin.

According to some implementations, a method of automatically preparing a tooth in a mouth of a patient to receive a custom crown using a robotic system includes attaching a rigid grounding member to a fixed position within the mouth of the patient; obtaining a pre-shaped virtual model of the mouth of the patient with the rigid grounding member therein; coupling a grounding arm of the robotic system to the rigid grounding member in the mouth of the patient, thereby establishing an origin for the mouth of the patient; developing a plan for automatically moving one or more tools relative to the established origin to shape the tooth in the mouth of the patient to receive the custom crown; and in response to a working arm of the robotic system being coupled with at least one of the one or more tools, implementing the developed plan by automatically moving at least a portion of the working arm according to the developed plan, thereby shaping the tooth in the mouth of the patient such that the tooth is substantially shaped according to the developed plan.

According to some implementations, a method of preparing a tooth in a mouth of a patient to receive a custom crown using a robotic system includes attaching a rigid grounding member to a fixed position within the mouth of the patient; obtaining a pre-shaped virtual model of the mouth of the patient with the rigid grounding member therein; determining an invisible boundary wall to be established around the tooth in the mouth to be shaped; coupling a grounding arm of the robotic system to the rigid grounding member in the mouth of the patient, thereby establishing an origin for the mouth of the patient; in response to a working arm of the robotic system being coupled with a shaping tool, manually moving at least a portion of the working arm to shape the tooth in the mouth of the patient; automatically enforcing the determined invisible boundary wall by preventing the working arm from being moved in a manner that would cause a cutting portion of the shaping tool to move outside of the determined invisible boundary wall; monitoring, during the moving, a position of the grounding arm and the working arm to generate positional data related to the location of the cutting portion of the shaping tool relative to the established origin; and creating a post-shaped virtual model of at least a portion of the mouth of the patient based on the obtained pre-shaped virtual model and the generated positional data, the at least a portion of the mouth including the shaped tooth.

According to some implementations, a method of preparing a tooth in a mouth of a patient to receive a custom crown using a robotic system includes coupling a grounding arm of the robotic system to the mouth of the patient, thereby establishing an origin for the mouth of the patient; in response to a working arm of the robotic system being coupled with a shaping tool, manually moving at least a

5

portion of the working arm to shape the tooth in the mouth of the patient; monitoring, during the moving, a position of the grounding arm and the working arm to generate positional data related to the location of a cutting portion of the shaping tool relative to the established origin; and creating a post-shaped virtual model of at least a portion of the mouth of the patient based at least in part on the generated positional data.

According to some implementations, a method of modifying a denture to be coupled with a plurality of dental implants in a mouth of a patient as a hybrid prosthesis using a robotic system includes attaching a first rigid grounding member to a fixed position within the mouth of the patient and attaching a second rigid grounding member to the denture; obtaining a pre-operative virtual model of the mouth of the patient with the first rigid grounding member and the denture therein; removing the denture, with the second rigid grounding member attached thereto, from the mouth of the patient; establishing an origin for the mouth of the patient by coupling a grounding arm of the robotic system to the first rigid grounding member in the mouth of the patient; using a working arm of the robotic system coupled to a dental-implant-driving tool, installing the plurality of dental implants in the mouth of the patient; monitoring, during the installing, a position of the grounding arm and the working arm to generate positional data related to the location of the dental-implant-driving tool relative to the established origin; creating a post-operative virtual model of at least a portion of the mouth of the patient based on the obtained pre-operative virtual model and the generated positional data; based at least in part on the post-operative virtual model, developing a plan for automatically modifying the denture such that the denture can be coupled with the installed plurality of dental implants; coupling the grounding arm of the robotic system to the second rigid grounding member attached to the denture; and using the working arm of the robotic system coupled to a drill-bit tool, modifying the denture by creating a plurality of holes such that the denture can be coupled with the installed plurality of dental implants as the hybrid prosthesis.

According to some implementations, a method of modifying a denture into a hybrid prosthesis using a robotic system includes obtaining a pre-operative virtual model of the mouth of the patient with the denture therein; removing the denture from the mouth of the patient; installing a plurality of dental implants in the mouth of the patient using a first tool controlled by the robotic system; monitoring, during the installing, a position of the first tool to generate positional data; creating a post-operative virtual model of at least a portion of the mouth of the patient based on the obtained pre-operative virtual model and the generated positional data; and based at least in part on the post-operative virtual model, modifying the denture by creating a plurality of holes therein using a second tool controlled by the robotic system such that the denture can be coupled with the installed plurality of dental implants as the hybrid prosthesis.

According to some implementations, a method of modifying a denture to be coupled with a plurality of dental implants in a mouth of a patient as a hybrid prosthesis using a robotic system includes obtaining a first virtual model of the mouth of the patient with the denture therein; removing the denture from the mouth of the patient; attaching a first rigid grounding member to a fixed position within the mouth of the patient; obtaining a second virtual model of the mouth of the patient with the first rigid grounding member therein; attaching a second rigid grounding member to the denture

6

outside of the mouth of the patient; obtaining a third virtual model of the denture with the second rigid grounding member attached thereto; establishing an origin for the mouth of the patient by coupling a grounding arm of the robotic system to the first rigid grounding member in the mouth of the patient; using a working arm of the robotic system coupled to a dental-implant-driving tool, installing the plurality of dental implants in the mouth of the patient; monitoring, during the installing, a position of the grounding arm and the working arm to generate positional data related to the location of the dental-implant-driving tool relative to the established origin; creating a fourth virtual model of at least a portion of the mouth of the patient based on the obtained second virtual model and the generated positional data; based at least in part on the first, the third, and the fourth virtual models, developing a plan for automatically modifying the denture such that the denture can be coupled with the installed plurality of dental implants; coupling the grounding arm of the robotic system to the second rigid grounding member attached to the denture; and using the working arm of the robotic system coupled to a drill-bit tool, modifying the denture by creating a plurality of holes such that the denture can be coupled with the installed plurality of dental implants as the hybrid prosthesis.

According to some implementations, a method of manufacturing a patient specific temporary prosthesis (PSTP) for use in manufacturing a permanent prosthesis for attachment to a dental implant installed in a mouth of a patient includes establishing an origin for a PSTP blank by coupling a grounding arm of a robotic system to the PSTP blank via a fixture; using a working arm of the robotic system coupled to a sculpting tool, modifying the PSTP blank such that the PSTP blank is transformed into the PSTP having a tooth-like shape suitable for attachment to the dental implant installed in the mouth of the patient; monitoring, during the modifying, a position of the grounding arm and the working arm to generate positional data related to the location of the sculpting tool relative to the established origin; and based at least in part on the generated positional data, creating a virtual model of at least a portion of the PSTP.

According to some implementations, a method of manufacturing a patient specific temporary prosthesis (PSTP) for use in manufacturing a permanent prosthesis for attachment to a dental implant installed in a mouth of a patient includes establishing an origin for a PSTP blank by coupling a grounding arm of a robotic system to the PSTP blank via a fixture; using a working arm of the robotic system coupled to a sculpting tool, modifying the PSTP blank such that the PSTP blank is transformed into the PSTP having a tooth-like shape suitable for attachment to the dental implant installed in the mouth of the patient; monitoring, during the modifying, a position of the grounding arm and the working arm to generate positional data related to the location of the sculpting tool relative to the established origin; based at least in part on the generated positional data, creating a virtual model of at least a portion of the PSTP; attaching the PSTP to the dental implant in the mouth of the patient; permitting gingival tissue surrounding the PSTP to heal in the mouth of the patient; in response to the healed gingival tissue surrounding the PSTP in the mouth of the patient satisfying a threshold, manufacturing the permanent prosthesis as a replica of the PSTP using the created virtual model; in response to the healed gingival tissue surrounding the PSTP in the mouth of the patient not satisfying the threshold: (i) physically modifying the PSTP; (ii) scanning the modified PSTP to obtain a modified virtual model of at least a portion of the modified PSTP; and (iii) manufacturing the permanent

prosthesis as a replica of the modified PSTP using the obtained modified virtual model.

A method of using a robotic system to automatically create a socket in a jawbone of a patient for receiving a dental implant therein including attaching a rigid grounding member to a fixed position within the mouth of the patient. A pre-operative virtual model of the mouth of the patient with the rigid grounding member therein is obtained. A grounding arm of the robotic system is coupled to the rigid grounding member in the mouth of the patient, thereby establishing an origin for the mouth of the patient. A plan for automatically moving two or more of a plurality of surgical tools relative to the established origin is developed to create the socket in the jawbone of the patient. A first one of the plurality of surgical tools is attached to a working arm of the robotic system. A first portion of the developed plan is executed by automatically moving the first one of the plurality of surgical tools via the working arm of the robotic system, thereby starting to create the socket in the jawbone of the patient according to the developed plan. Data is received from one or more sensors of the robotic system indicative of at least one of a torque or a force required to implement the first portion of the developed plan. A second portion of the developed plan is modified based on the received data. The modified second portion of the developed plan is executed by automatically moving a second one of the plurality of surgical tools via the working arm of the robotic system, thereby completing the socket in the jawbone of the patient according to the modified plan.

A method of using a robotic system includes developing a plan for automatically moving one or more of a plurality of surgical tools relative to an established origin of the robotic system to perform a surgical procedure in a mouth of a patient. A first one of the plurality of surgical tools is attached to a working arm of the robotic system. A first portion of the developed plan is executed. During the execution of the first portion of the developed plan, data is received from one or more sensors of the robotic system. A second portion of the developed plan is modified based on the received data.

Additional aspects of the present disclosure will be apparent to those of ordinary skill in the art in view of the detailed description of various implementations, which is made with reference to the drawings, a brief description of which is provided below.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other advantages of the disclosure will become apparent upon reading the following detailed description and upon reference to the drawings.

FIG. 1 is a perspective view of a robotic system having a working arm and a grounding arm according to some implementations of the present disclosure;

FIG. 2 is a perspective view of a portion of the working arm of the robotic system of FIG. 1 coupled with a surgical tool;

FIG. 3 is a perspective view of a portion of the grounding arm of the robotic system of FIG. 1;

FIG. 4 is a perspective view of a rigid grounding member to be coupled with a mouth of a patient for use with the robotic system of FIG. 1;

FIG. 5 is a perspective view of the rigid grounding member of FIG. 4 being coupled to a mouth of a patient and a scanner for scanning the mouth of the patient;

FIG. 6 is a perspective view of the grounding arm of the robotic system of FIG. 1 being coupled with the rigid grounding member that was coupled to the mouth of the patient;

FIG. 7 is a perspective view of the working arm and coupled surgical tool being used to perform a procedure in the mouth of the patient;

FIG. 8A is an illustrative perspective view of the surgical tool coupled to the working arm of the robotic system bumping into an invisible barrier wall according to some implementations of the present disclosure;

FIG. 8B is the illustrative perspective view of FIG. 8A overlaid on top of the perspective view of FIG. 7 illustrating a use of the invisible barrier wall during the manual performance of a surgical procedure according to some implementations of the present disclosure; and

FIG. 9 illustrates a modified or post-operative virtual three-dimensional model of a mouth of a patient displayed on a display device of the robotic system of FIG. 1 according to some implementations of the present disclosure.

While the present disclosure is susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and will be described in detail herein. It should be understood, however, that the present disclosure is not intended to be limited to the particular forms disclosed. Rather, the present disclosure is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the present disclosure as defined by the appended claims.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

Referring to FIG. 1, a robotic system 100 of the present disclosure can be used in a variety of manners to perform a variety of surgical and/or non-surgical procedures. Once the robotic system 100 is registered to a patient 10 and loaded with a pre-determined surgical plan, the robotic system 100 is ready to automatically carry out one or more surgical procedures or portions thereof. By automatically, it is meant that the robotic system can, without interruption or input from a human (e.g., other than registering the robotic system 100, loading the pre-determined surgical plan, and in some implementations hitting a start button), perform a surgical procedure or portion thereof.

Additionally, the robotic system 100 can be manually manipulated by, for example, an oral surgeon to be used in performing one or more surgical procedures. Manually performing a surgical procedure using the robotic system 100 aids the surgeon as compared to performing a manually procedure without the robotic system 100 as the robotic system 100 supports the weight of the tools (e.g., tool 155 and surgical tool-bits 132 coupled thereto) used by the surgeon during the often lengthy surgery. Further, the robotic system 100 can be configured to aid the surgeon by preventing the surgeon from moving a surgical tool-bit 132 of the robotic system 100 in a manner that is inconsistent with a general plan or outline for the procedure. For example, an invisible barrier wall (e.g., invisible barrier wall 450 shown in FIGS. 8A and 8B) and/or area can be established prior to a procedure being conducted such that the robotic system 100 prevents manual manipulation of the tool 155 and tool-bit 132 coupled thereto in a manner that would cause the surgical tool-bit 132 to move past the invisible barrier wall/area 450 (e.g., and into a nerve, the wrong tooth, the palate of the mouth of the patient, the cheek of the patient, etc.). Further, the robotic system 100 can implement

haptic feedback to indicate to a manual user **400** (FIGS. 7, **8A**, **8B**) of the robotic system **100** that the user **400** (e.g., the surgeon) is attempting to move the surgical tool outside of the accepted working space (e.g., past the invisible barrier wall/area **450**). For example, the robotic system **100** can vibrate the tool **155** and/or make an audible noise to indicate that the surgeon **400** is attempting to move the tool **155** and surgical tool-bit **132** coupled thereto past the predefined limits for the particular procedure (see FIGS. **8A** and **8B**). Further, the robotic system **100** can improve a surgeon's fidelity by increasing the resolution with which the surgeon can operate as compared to a surgeon not using the robotic system **100**. That is, using the robotic system **100**, the surgeon is able to move surgical tools coupled thereto with a higher degree of accuracy and in relatively smaller increments (i.e., higher resolution) as compared to the accuracy and increment size the surgeon can move surgical tools without using the robotic system **100**.

Further, during manual manipulation of the robotic system **100**, the robotic system **100** can monitor movements of the robotic system **100** and develop a positional data set indicative of the performed procedure. That is, the robotic system **100** can trace/follow a path taken by the tool **155** and/or by the surgical tool-bit **132** coupled thereto (or at least a tip portion of the surgical tool-bit **132**) and record data indicative of that traced path. As such, with knowledge of the geometry of the used surgical tool-bit(s) **132** and an established origin, O, (see FIGS. **4** and **8B**) for the mouth **12** of the patient **10** and/or of the robotic system **100**, the final patient situation can be determined (e.g., a post-operative virtual three-dimensional model **326** of at least a portion of the mouth **12** of the patient **10** as modified during the procedure as shown in FIG. **9**). For example, if the robotic system **100** is used to remove bone, the positional data collected by the robotic system **100** would be indicative of where the bone removal tool-bit **132** physically traveled/went relative to the established origin, O, of the mouth during the procedure (e.g., which is related to the bone in the mouth **12** of the patient **10**) and can thereby be used to develop a post-operative virtual three-dimensional model (similar to the post-operative virtual three-dimensional model **326** shown in FIG. **9**) of at least a portion of the mouth **12** of the patient **10** illustrating the removed bone. This virtual three-dimensional model is thus created without having to take a post-operational intraoral scan of the patient **10**—sparing the patient **10** this added scanning step.

Additional details on the robotic system **100** and uses of the robotic system **100** are described below in various Sections herein. While the disclosure is broken into these Sections including various implementations having described elements, any portion and/or any element contained in any Section and/or any implementation can be combined and/or modified with any portion and/or any element in any other Section and/or any other implementation described herein.

Components and General Operation Robotic System **100**

As shown in FIG. **1**, the robotic system **100** includes a base **120**, a working arm **140**, and a grounding arm **160**. The base **120** can also be referred to as a cabinet for housing a multitude of elements therein, where at least some of the elements housed therein are coupled together to perform one or more functions/operations. The base **120** rests on a ground surface **105** (e.g., a floor of a dental surgical room). The base **120** can be fixed to the ground surface **105** or moveable with respect to the ground surface **105**. In the implementations when the base **120** is moveable with respect to the ground surface **105**, a bottom side of the base

120 includes one or more casters or rollers (not shown). Alternatively or additionally to the base **120** resting on and/or being coupled to the ground surface **105**, the base can be coupled to a wall surface **107** (e.g., a wall of the dental surgical room). Preferably, the base **120** is mounted to the ground surface **105** and/or the wall **107** to aid in preventing the robotic system **100** from tipping over during use thereof.

The base **120** houses and/or is coupled to/associated with a computer **121**, a display device **122**, input devices **124a**, **124b**, a surgical tool tray **130**, and storage drawers **135**. The computer **121** is communicatively connected with the display device **122**, the input devices **124a**, **124b**, the working arm **140** and the grounding arm **160**. The computer **121** can include controllers, processors, memory devices, communication devices (e.g., wireless, wired, etc.), etc. configured to run/execute one or more software programs (e.g., robotic system control software programs, dental surgical planning software programs, abutment design software programs, crown design software programs, etc.). The computer **121** is specially programmed and improved for controlling and/or tracking/tracing the working arm **140** and/or the grounding arm **160** of the robotic system **100**. Alternatively, the computer **121** can be a general purpose computer capable of executing specific software to control and/or track the working arm **140** and/or the grounding arm **160** of the robotic system **100**.

The input devices **124a**, **124b** are shown as being a keyboard and a mouse for use in operating the computer **121**. Additional input devices can be used such as, for example, a joystick, a wireless or wired electronic pen, a touch screen overlaid on the display device **122**, a foot pedal, etc.

The surgical tool tray **130** stores a multitude of surgical tools or surgical tool-bits **132** therein for use in a variety of procedures (e.g., creation of an osteotomy, implant placement, bone shaving, tooth-crown prepping, probing/mechanical sensing, denture modification, provisional restoration shaping, abutment shaping, etc.). While only four surgical tool-bits **132** are shown, any number of surgical tool-bits **132** can be included in the surgical tool tray **130** (e.g., one surgical tool-bit, two surgical tool-bits, ten surgical tool-bits, thirty surgical tool-bits, etc.). The surgical tool-bits **132** can include drill-bit tools (e.g., to create sockets and/or openings in bone), tapping tools (e.g., to create threads in bone sockets/openings), dental-implant-driving tools, rotating mill tools, saw tools, probe tools, mechanical sensing tool-bits, scalpel/knife tools, or any combination thereof. In some implementations, the base **120** stores a multitude of surgical tool trays **130** in one of the storage drawers **135**. In such implementations, depending on the procedure being conducted using the robotic system **100**, a user (e.g., oral surgeon, clinician, dental assistant, etc.) connects the proper one of the surgical tool trays **130** to the base **120** and puts any extra surgical tool trays **130** back into the storage drawer **135** for future use and/or cleaning. The surgical tools **132** on the surgical tool tray **130** are arranged in a known manner such that the robotic system **100** can cause the working arm **140** to automatically move and pick-up a desired one of the surgical tool-bits **132**. In some implementations, to avoid the robotic system **100** picking-up the wrong surgical tool-bit **132**, the surgical tool tray **130** is designed such that the surgical tool tray **130** can only connect with the base **120** in one orientation. Further, in some implementations, each surgical tool-bit **132** is designed to only be coupled with one known location on the surgical tool tray **130**. Yet in other implementations, an

11

operator of the robotic system **100** manually couples the working arm **140** with a desired one of the surgical tool-bits **132**.

The working arm **140** has a first end **141a** that extends from the base **120** and a second opposing end **141b** that is configured to be coupled with one of the surgical tool-bits **132** via a tool **155** to be used in performing a procedure. Between the first and the second ends **141a,b**, the working arm **140** includes a multitude of rigid arm members **145** coupled together by a multitude of flexible joint members **150**. Each of the rigid arm members **145** can have a fixed length or be capable of having a variable length, such as, for example, having a telescoping configuration (not shown). Such a telescoping configuration provides added flexibility for the robotic system **100** to reach further from the base **120** during the performance of a procedure. As shown, the working arm **140** is directly coupled to the base **120** via one of the flexible joint members **150**, although the working arm **140** can be directly coupled to the base **120** via one of the rigid arm members **145** instead. The rigid arm members **145** can be made of a variety of materials such as, for example, titanium, plastic, steel, of any combination thereof.

Each of the flexible joint members **150** is configured to mate one of the rigid arm members **145** to another one of the rigid arm members **145** or to the base **120**. Each of the flexible joint members **150** includes one or more motors therein for causing relative movement of the ones of the rigid arm members **145** mated to the flexible joint member **150**. For example, each of the flexible joint members **150** includes an electric servo motor, an electric rotary motor, etc. As such, in response to a command from the computer **121**, for example, automatically executing a preplanned surgical procedure, the flexible joint member **150** can cause one of the rigid arm members **145** to rotate/pivot relative to another one of the rigid arm members **145** coupled to the same flexible joint member **150**. Depending on the number and/or type of motor(s) in the flexible joint member **150**, the relative rotating/pivoting can be one dimensional, two dimensional, or three dimensional. That is, one of the rigid arm members **145** can be caused to rotate/pivot forward and backward relative to the other one of the rigid arm members **145** (e.g., pitching), rotate/pivot left and right relative to the other one of the rigid arm members **145** (e.g., swaying), and/or rotate/pivot side-to-side relative to the other one of the rigid arm members **145** (e.g., rolling).

As shown, the working arm **140** includes four rigid arm members **145** and four flexible joint members **150**. With the ability for each of the four flexible joint members **150** to rotate/pivot the rigid arm members **145** mated thereto as described above, the second end **141b** of the working arm **140** and/or the tool **155** is able to move with at least six degrees of freedom relative to the base **120** (e.g., three degrees of rotational freedom and three degrees of translational freedom). It is contemplated that the number of rigid arm members **145** and flexible joint members **150** included in the working arm **140** can vary. As the number of the rigid arm members **145** and flexible joint members **150** decreases, so does the flexibility of the working arm **140**. Similarly, as the number of the rigid arm members **145** and flexible joint members **150** increases, so does the flexibility of the working arm **140**. For example, additional fine-tuning-flexible joint members **150** can be included that have a relatively smaller range of motion to precisely place the tool **155** and the surgical tool-bits **132** coupled thereto in the mouth **12** of the patient **10** in a desired location. Specifically, in some implementations, the surgical tool-bits **132** can be placed with less than a 0.5 millimeter margin of error from a desired

12

target placement. In some other implementations, the surgical tool-bits **132** can be placed with less than a 0.1 millimeter margin of error from a desired target placement.

In addition to each of the flexible joint members **150** including one or more motors therein, each of the flexible joint members **150** includes one or more sensors for sensing the relative positional relationship between the rigid arm member(s) **145** coupled thereto. That is, for example, each one of the flexible joint members **150** includes one or more sensors that can determine the relative angular positional relationship between the two of the rigid arm members **145** coupled thereto relative to an X-Y-Z space having its origin at the center of the flexible joint member **150**. Thus, in response to a user of the robotic system **100** moving one of the rigid arm members **145**, the one or more sensors in the flexible joint member **150** coupled to the manually moved rigid arm member **145** are configured to sense that movement and generate data representative of the new location of the rigid arm member **145** relative to an origin of the flexible joint member **150** and/or relative to the origin, O, of the robotic system **100** and/or of the mouth **12** of the patient **10**. Such data is transmitted (wirelessly and/or via a wire) to the computer **121** for processing. For another example, in response to an operator **400** (FIG. 7) manually moving the second end **141b** and/or the tool **155** of the working arm **140** such that some or all of the rigid arm members **145** are moved relative to the base **120**, each of the flexible joint members **150** generates data that is transmitted to the computer **121** for processing. The computer **121** is configured to execute a tracing software program and/or algorithm that is able process the data from each of the flexible joint members **150** to determine the location of the second end **141b** of the working arm **140** (or any portion of any tool **155** and/or surgical tool-bit **132** coupled thereto) relative one or more established origins, O, for the robotic system **100** and/or for the mouth **12** of the patient **10**. As such, the robotic system **100** is capable of tracking movement of the working arm **140**.

The grounding arm **160** has a first end **161a** that extends from the base **120** and a second opposing end **161b** that is configured to be coupled with a rigid grounding member **200** (FIG. 4) to establish the origin, O, for the robotic system **100** and/or for the mouth **12** of the patient **10**. Between the first and the second ends **161a,b**, the grounding arm **160** includes a multitude of rigid arm members **165** coupled together by a multitude of flexible joint members **170**. The rigid arm members **165** are the same as, or similar to, the rigid arm members **145** and the flexible joint members **170** are the same as, or similar to, the flexible joint members **150** described herein.

Now referring to FIG. 2, the second end **141b** of the working arm **140** is shown in detail. Specifically, a portion of two rigid arm members **145a,b** coupled by a flexible joint member **150** is shown. The rigid arm member **145b** has a first end **146a** coupled with the flexible joint member **150** and a second end **146b** that is coupled with a coupler **147**. The coupler **147** is rigidly attached to the second end **146b** of the rigid arm member **145b** and designed to removably receive a portion of the tool **155** therein. As shown in FIG. 2, the tool **155** is a drill or driving tool for rotating a surgical tool-bit **132a**. Coupling the tool **155** to the coupler **147** can be purely mechanical and/or electrical. That is, the coupling of the tool **155** with the coupler **147** can include supplying power to the tool **155** through the coupler **147** or the tool **155** can be self-powered (e.g., via one or more disposable and/or rechargeable batteries). The connection between the coupler **147** and the tool **155** can be a press fit connection, a snap-in

connection, a threaded connection, a magnetic connection, a friction connection, a tongue and groove connection, or any combination thereof such that the tool 155 is removably and securely coupled to the coupler 147 in a known and repeatable manner. In some implementations, the coupling of the tool 155 with the working arm 140 creates a communicative connection where the tool 155 is able to talk with the computer 121 through the working arm 140, such that the identity of the tool 155 is disclosed to the computer 121. As such, the computer learns the identity and size and shape of the tool 155 which is needed to precisely trace the movements of the tool 155 and any surgical tool-bit 132 coupled thereto. Alternatively, the working arm 140 is designed to only connect with a single tool 155 such that identification of the tool 155 is unnecessary. Yet in further alternative implementations, the robotic system 100 runs a check prior to conducting a procedure to confirm that the correct tool 155 is coupled to the working arm 140.

In some implementations, the tool 155 includes a multitude of buttons 156. The buttons 156 can be preprogrammed and/or programmable to start operation of the tool 155 (e.g., a start/ON button), to end operation of the tool 155 (e.g., a stop/OFF button), to reverse rotation of the tool 155 (e.g., forward/backward rotation), etc. One or more lights (e.g., LEDs) can be included in the tool 155 and positioned adjacent to each button 156 to indicate whether the button 156 is activated or not. In some implementations, the tool 155 includes a release button or mechanism 157 for use in aiding in the removal of the surgical tool-bit 132a from the tool 155. In other implementations, the surgical tool-bit 132a can simply be pulled out of the tool 155 without having to press the release button 157.

Now referring to FIG. 3, the second end 161b of the grounding arm 160 is shown in detail. Specifically, a portion of a rigid arm member 165a is coupled by a flexible joint member 170 to a grounding probe 180. The grounding probe 180 has a first end 180a coupled with the flexible joint member 170 and a second end 180b designed to couple with the rigid grounding member 200 (FIG. 4) in a removable and repeatable fashion. As shown in FIG. 3, the second end 180b of the grounding probe 180 includes a pair of biased locking bearings 182a,b. The locking bearings 182a,b are biased outward away from a central axis, YC, of the second end 180b of the grounding probe 180. As such, the locking bearings 182a,b can be forced inward toward the central axis, YC, to allow the second end 180b of the grounding probe 180 to be slid into a receiving bore 222 of the rigid grounding member 200 (FIG. 4) in a removable and repeatable fashion.

Registering the Robotic System 100 to the Mouth 12 of the Patient 10 Using the Rigid Grounding Member 200

Referring to FIG. 4, the rigid grounding member 200 is shown as including a body 205 and a coupling post 220. The body 205 includes a first leg 207a and a second leg 207b coupled together by a base 209 therebetween. The base has an upper surface 209a and a bottom surface 209b. Protruding generally upward from the upper surface 209a of the base 209 is the coupling post 220. The body 205 and the coupling post 220 can be two separate and distinct parts that are attached together or they can be integrally formed as a monolithic component. The coupling post 220 includes the receiving bore 222 therein for receiving the second end 180b of the grounding probe 180 therethrough when grounding the grounding arm 160 of the robotic system 100 to the mouth 12 of the patient 10 (e.g., when the rigid grounding member 200 is installed in the mouth 12 of the patient 10). The receiving bore 222 has a central axis, XC, along which

the origin, O, for the robotic system 100 and/or the mouth 12 of the patient 10 can be established. In some implementations, the origin, O, is established at a center of the receiving bore along the central axis, XC. In some alternative implementations, the origin, O, is established at any point along the central axis, XC, for example, at either end opening of the receiving bore 222.

The first leg 207a includes a threaded throughbore 208 that receives a fastener 230 (e.g., surgical dental screw, dental bolt, etc.). While not shown, the second leg 207b can also include a threaded throughbore the same as, or similar to, the threaded throughbore 208 for receiving the fastener 230 therein and/or another fastener (not shown). While the rigid grounding member 200 is shown as having a specific shape and size, various other shapes, sizes, and arrangements for the rigid grounding member 200 are contemplated, such that the rigid grounding member 200 can be attached to the mouth 12 of the patient 10 and provide a means for coupling the grounding probe 180 thereto in a removable and repeatable fashion.

According to some implementations, in order to register the robotic system 100 to the mouth 12 of the patient 10 and establish the origin, O, for use during a procedure using the robotic system 100, the rigid grounding member 200 is installed into the mouth 12 of the patient 10. As shown in FIG. 5, the mouth 12 of the patient 10 includes teeth 14, a jawbone 16, and soft tissue 18 (e.g., gingival tissue), where tooth 14a is selected to be coupled with the rigid grounding member 200. As shown in FIG. 6, the mouth 12 further includes a surgical site 20 (e.g., location to receive a dental implant, permanent abutment, and permanent crown), where teeth 14b and 14c are positioned adjacent to the surgical site 20.

While the rigid grounding member 200 is attached to the tooth 14a, the rigid grounding member 200 can be attached to any of the other teeth 14 in the mouth 12 and/or to the jawbone 16 of the patient 10. To attach the rigid grounding member 200 to the tooth 14a, the rigid grounding member 200 is placed on the tooth 14a. Specifically, for example, the rigid grounding member 200 is positioned in the mouth 12 of the patient 10 such that (i) the bottom surface 209b of the base 209 is positioned generally adjacent to an occlusal surface of the tooth 14a, (ii) the first leg 207a is positioned generally adjacent to a lingual surface of the tooth 14a, and (iii) the second leg 207b is positioned generally adjacent to a buccal surface of the tooth 14a, as shown in FIG. 5. With the rigid grounding member 200 so positioned, the fastener 230 is threaded into the threaded throughbore 208 of the first leg 207a to rigidly lock the rigid grounding member 200 in place against the tooth 14a. In some implementations, the fastener 230 is tightened such that the fastener 230 does not penetrate the tooth 14a, the soft tissue 18, and/or the jawbone 16. However, in some alternative implementations, the fastener 230 does penetrate the tooth 14a, the soft tissue 18, the jawbone 16, or any combination thereof.

With the rigid grounding member 200 attached to the tooth 14a, a scan of the mouth 12 of the patient 10 is taken using a scanner/camera 300 as shown in FIG. 5. Depending on the type of procedure being planned for implementation using the robotic system 100, the scan of the mouth 12 can be an intraoral surface scan using an intraoral scanner, a CT scan using a CT scanner (such as, for example, a cone-beam computed tomography (CBCT) scanner also known as a dental CBCT scanner), or a combination thereof. The scanning of the mouth 12 with the rigid grounding member 200 therein, allows for the generation of the pre-operative three-dimensional virtual model 325 (FIG. 1) of the mouth 12 of

the patient 10 to be generated. Such a virtual model can be used for developing a surgical plan and/or for designing components to be mated on a dental implant installed in the mouth 12 of the patient 10. Specifically, the virtual model 325 includes a virtual rigid grounding member 200' (FIG. 1) that is used to establish the origin, O, of a coordinate system to be used by the robotic system 100 when conducting a procedure.

After the scanning of the mouth 12, the robotic system 100 is grounded to the mouth 12 of the patient 10. Specifically, the second end 180b of the grounding probe 180 is mated with the rigid grounding member 200 by positioning and/or sliding the second end 180b of the grounding probe 180 into the receiving bore 222 of the coupling post 220 of the rigid grounding member 200. The second end 180b is slid until the locking bearings 182a,b are slid through and outside of the receiving bore 222 and biased outward away from the central axis, YC, (FIG. 3) such that the grounding probe 180 cannot readily be removed from the receiving bore 222. In some implementations, tactile feedback is used to indicate that the grounding probe 180 is fully engaged with the rigid grounding member 200 and properly positioned therein. For example, when the grounding probe 180 is fully engaged, the locking bearings 182a,b can snap into place making an audible sound and/or a vibrating click.

By readily be removed, it is meant that to remove the grounding probe 180 from its engagement with the rigid grounding member 200, the locking bearings 182a,b need to be actuated by being pressed inward towards the central axis, YC, to allow the grounding probe 180 to be slid out of the receiving bore 222. Alternatively, the grounding probe 180 can be removed from its engagement with the rigid grounding member 200 by pulling the grounding probe 180 with a sufficient amount of force to overcome the biasing force of the locking bearings 182a,b, thereby causing the locking bearings 182a,b to be forced inward towards the central axis, YC, and allow the removal of the grounding probe 180 from engagement with the rigid grounding member 200.

As best shown in FIG. 6, a length, L180b, of the second end 180b of the grounding probe 180 is designed such that once the grounding probe 180 is properly engaged with the coupling post 220 of the rigid grounding member 200, the grounding probe 180 does not have any or very little translational play therein. That means that the grounding probe 180 cannot slide and/or move laterally (e.g., translation) along the central axis, YC, when the grounding probe 180 is engaged with the rigid grounding member 200. However, the grounding probe 180 is allowed to rotate within the receiving bore 222 about the central axis, YC. Such a connection between the grounding probe 180 and the rigid grounding member 200 aids the robotic system 100 in maintaining the known origin, O, based on the location of the rigid grounding member 200 in the mouth 12 of the patient 10.

With the robotic system 100 grounded to the mouth 12 of the patient 10 via the rigid grounding member 200 and the grounding probe 180 (coupled to the grounding arm 160 of the robotic system 100), the robotic system 100 is ready to automatically implement a preplanned procedure and/or to allow an operator 400 to perform a manual and/or a semi-manual procedure that is tracked/traced by the robotic system 100. In the case of using the robotic system 100 to automatically implement/conduct a preplanned procedure, the preplanned procedure must first be planned, for example, using a dental surgical planning software program, as described in the following Section.

Planning a Surgical Plan for Automatic Implementation by the Robotic System 100

As discussed above, the mouth 12 of the patient 10 is scanned with the rigid grounding member 200 therein. The scan data generated from that scan (e.g., intraoral surface scan, CT scan, dental CBCT scan, X-ray scan, a combination thereof, etc.) is imported and/or sent to the computer 121, or another computer, that executes and/or runs a dental surgical planning software program. As shown in FIG. 1, the surgical planning software program is designed to display on the display device 122 the pre-operative three-dimensional virtual model 325 of at least a portion of the mouth 12 of the patient 10. The pre-operative three-dimensional virtual model of the virtual mouth 12' includes virtual teeth 14', virtual soft tissue 18', a virtual surgical site 20', a virtual rigid grounding member 200', and in some implementations where a dental CBCT scan and/or X-ray scan is taken, virtual bone 16' (e.g., jawbone), which correspond with the teeth 14, the soft tissue 18, the surgical site 20, the rigid grounding member 200, and the bone 16 in the actual mouth 12 of the patient 10.

Depending on the type of procedure that is to be conducted in the mouth 12 of the patient 10, the dental surgical planning software program is designed to automatically and/or with some input from an operator (e.g., operator 400 shown in FIG. 7), develop a surgical plan for conducting the desired procedure automatically using one or more of the surgical tool-bits 132 attached to the tool 155 of the working arm 140 of the robotic system 100. Specifically, the dental surgical planning software program is designed to develop a set of instructions and/or movements for the working arm 140 to make relative to the grounding arm 160 (e.g., relative to the second end 180b of the grounding probe 180), which is positioned at a known location relative to the rigid grounding member 200 in the mouth 12 of the patient 10 (e.g., the established origin, O along the central axis, YC, shown in FIG. 4). The developed set of instructions includes directions as to what type and/or size of tool or tools to be used during the surgical procedure. The developed set of instructions also includes an order for using the tools when multiple tools are to be used. For example, if the desired procedure is an osteotomy, the developed instructions include which surgical drill-bit tool or tools 132 to use. Specifically, in an exemplary osteotomy, the instructions may direct the robotic system 100 to first use a first surgical drill-bit tool 132 having a first diameter and a first length to start the procedure (e.g., to create an initial socket/opening in the jawbone), followed by an instruction for the robotic system 100 to switch to a second surgical drill-bit tool 132 having a second (e.g., relatively larger) diameter and a second length (e.g., the same as or different than the first length) to continue the procedure (e.g., to enlarge a diameter of the created socket/opening in the jawbone), etc. A subsequent instruction may include for the robotic system 100 to switch to a surgical tapping tool 132 to tap (e.g., create threads) the previously created socket/opening in the jawbone. In some implementations, the surgical system 100 automatically and without operator input switches the surgical tool-bits 132 to the tool 155; and in some alternative implementations, an operator manually attaches and detaches the surgical tool-bits 132 to the tool 155.

The development of the surgical plan by the dental surgical planning software program can be completely autonomous after receipt of the scan data (e.g., pre-operative virtual three-dimensional model 325), or the development can involve some input from an operator. For example, the dental surgical planning software program may require an

input from the operator such as the type of procedure to be planned (e.g., creation of an osteotomy, implant placement, bone shaving, etc.), the location and orientation for a desired central axis of the implant to be placed (e.g., to avoid a nerve in the mouth **12** and/or to avoid an area of low density bone in the mouth **12**), the manufacturer of the implant to be placed, the size of the implant to be placed, etc.

Once the surgical plan is developed using the dental surgical planning software program, the robotic system **100** is ready to conduct/implement the surgical plan using one or more of the surgical tool-bits **132**. In some implementations, the computer **121** that controls the working arm **140** and the grounding arm **160** also executes and runs the surgical planning software program. In such implementations, the developed surgical plan is automatically loaded and ready to be automatically implemented by the robotic system **100**, for example, in response to an operator clicking a start button on the display device **122**. In alternative implementations where a different computer executes/runs the dental surgical planning software program, the developed surgical plan needs to be sent to and/or loaded into the robotic system **100**.

As shown in FIG. 7, after the surgical plan is initiated, the working arm **140** moves into place (e.g., at least partially into the mouth **12** of the patient **10**) relative to the grounding arm **160** and starts to perform the procedure automatically at the surgical site **20** using one or more of the surgical tool-bits **132**.

Defining the Invisible Barrier Wall/Area **450** for Confining Movement of the Robotic System **100**

As discussed herein, instead of having the robotic system **100** conduct a surgical procedure automatically, the robotic system **100** can be used manually such that the operator **400** (FIGS. 7, **8A**, **8B**) causes the working arm **140** and the attached surgical tool-bit **132** to move relative to the patient **10**. In such implementations, the invisible barrier wall/area **450** can be established prior to conducting the procedure. As shown in FIG. **8A**, the invisible barrier wall/area **450** is shown without the mouth **12** of the patient **10** for illustrative purposes, whereas FIG. **8B** illustrates the same invisible barrier wall/area **450** overlaid in the mouth **12** of the patient **10**.

The invisible barrier wall/area **450** can be established and/or developed using the surgical planning software program described herein as part of a surgical plan. In such implementations, for a semi-manual procedure to be conducted by an operator using (e.g., manually manipulating) the robotic system **100**, the invisible barrier wall/area **450** establishes a boundary for the working arm **140**, and specifically the surgical tool-bit **132** coupled thereto, when the surgical tool-bit **132** is near the patient **10** and/or positioned inside of the mouth **12** of the patient **10**. As such, the invisible barrier wall/area **450** can aid in preventing the operator (e.g., oral surgeon) from moving the tool **155** in a manner that would cause the surgical tool-bit **132** and/or any portion of the working arm **140** (e.g., including the tool **155**) to interfere with the mouth **12** of the patient **10**.

By interfere, it is meant, for example, that working arm **140** is bumped into teeth **14** of the patient **10** not being addressed by the procedure being conducted. For another example, by interfere, it is meant that the surgical tool-bit **132** is moved (e.g., vertically up and/or down, side-to-side, etc.) too far into the jawbone **16** of the patient **10** when, for example, the robotic system **100** is being used to perform a semi-manual procedure, such as, for example, creation of an osteotomy. As such, when the operator **400** is manually creating the osteotomy by manually moving the working arm **140**, the robotic system **100** implementing the invisible

barrier wall/area **450** allows the operator **400** to move the surgical tool-bit **132** as desired (e.g., vertically up and/or down, side-to-side, etc.) within the bounds of the invisible barrier wall/area **450**, but if the operator **400** attempts to move the surgical tool-bit **132** outside of and/or past the invisible barrier wall/area **450**, then the robotic system **100** actively prevents such a movement using, for example, the motors in the flexible joint members **150**. For example, as illustrated in FIGS. **8A** and **8B**, the operator **400** is attempting to cause the surgical tool-bit **132** to be moved in the direction of arrow A (e.g., downward relative to the orientation of FIG. **8B**) through the invisible barrier wall/area **450**. However, because the surgical system **100** is actively enforcing the invisible barrier wall/area **450**, the surgical system **100** causes the working arm **140**, the tool **155**, the surgical tool-bit **132**, or any combination thereof, to vibrate (e.g., tactile feedback) indicating that the operator is attempting to move the surgical tool **132** past the invisible barrier wall/area **450**, which is not allowed. Use of such an invisible barrier wall/area **450** can be used, for example, to allow an operator (e.g., dental surgeon) to perform a free-form-shaped osteotomy where the operator is permitted to sculpt the osteotomy (e.g., move a surgical rotating mill tool **132** vertically up and/or down and side-to-side)—as opposed to using a set of stepped drill bits that are only moved vertically along a single central axis. As such, the operator can in real-time manually modify/update a surgical plan based on the received tactile feedback and/or other information (e.g., a level of torque needed to maintain a desired or preset drill speed during the procedure, a level of force needed to advance the surgical tool-bit **132** during the procedure, etc.).

While the invisible barrier wall/area **450** is shown as having an open top, alternative invisible barrier wall/areas can have invisible walls/invisible surfaces on all sides such that at least a portion of the working arm **140** (e.g., a tip of the surgical tool-bit **132**) is completely enclosed within the invisible barrier wall/area during the entire procedure being performed using the robotic system **100**. As such, the invisible barrier wall/area can extend outside of the mouth **12** of the patient **10**. Such an invisible barrier wall/area can aid in preventing a portion of the working arm **140** from being bumped into the face or head or chest of the patient **10**, among other things.

The invisible barrier wall/area **450** is shown in FIGS. **8A** and **8B** in dashed lines to indicate that the invisible barrier wall/area **450** is not actually visible to the operator of the robotic system **100** in the mouth **12** of the patient **10** during the procedure. However, in some implementations, a virtual representation of the invisible barrier wall/area **450** can be displayed on the display device **122** and/or on another display device during the procedure. For example, a virtual representation of the invisible barrier wall/area **450** can be displayed relative to a virtual model (e.g., the pre-operative three-dimensional virtual model **325**) of the mouth **12** of the patient. For another example, a virtual representation of the invisible barrier wall/area **450** can be displayed relative to a live video feed of the mouth **12** of the patient **10**. For yet another example, a virtual representation of the invisible barrier wall/area **450** can be displayed relative to a picture of the mouth **12** of the patient **10**. The displaying of a virtual representation of the invisible barrier wall/area **450** allows the operator to visualize the invisible barrier wall/area **450** relative to the mouth **12** of the patient **10**, which can aid in the operator conducting and/or monitoring/supervising the procedure.

Monitoring/Tracing a Semi-Manual Procedure Using the Robotic System 100

The robotic system 100 can be used to perform a semi-manual procedure. By semi-manual it is meant that the robotic system 100 allows the operator 400 (FIGS. 7, 8A, 8B) of the robotic system 100 to manually manipulate/move the working arm 140 relative to the mouth 12 of the patient 10 to perform a procedure while at the same time maintain a level of control. For example, the robotic system 100 maintains control of the working arm 140 and the grounding arm 160 by supporting its own weight and/or monitoring/sensing the positions of the working arm 140 and the grounding arm 160 relative to the established origin, O (FIG. 8B).

As discussed herein, the working arm 140 includes a multitude of flexible joint members 150 and the grounding arm 160 includes a multitude of flexible joint members 170, where each of the flexible joint members 150, 170 includes one or more sensors for use in determining a position of at least a portion of the working arm 140 (e.g., a tip of the surgical tool-bit 132, etc.) and/or the grounding arm 160 (e.g., a tip of the grounding probe 180). For example, as the operator 400 moves the tool 155 (FIG. 8B), the sensors in the flexible joint members 150, 170 record data that is transmitted to the computer 121 for processing. The computer 121 runs/executes robotic control software that receives the data from the sensors and processes that data to determine a location of at least a portion of the working arm 140 (e.g., a tip of the surgical tool-bit 132) relative to the established origin, O (FIG. 8B).

For example, as shown in FIG. 8B, the origin, O, for the robotic system 100 is established as a central point along the central axis, XC, of the receiving bore 222 of the coupling post 220 and along the central axis, YC, of the second end 180b of the grounding probe 180. Alternatively, the origin, O, can be established at any location relative to the rigid grounding member 200, as the rigid grounding member 200 is fixed relative to the rest of the mouth 12 of the patient 10 in a known and recorded fashion (e.g., known and recorded during the scanning of the mouth 12 with the rigid grounding member 200 therein as described herein) when installed in the mouth 12.

As the operator 400 conducts a semi-manual procedure, with the robotic system 100 tracking/tracing every movement of the working arm 140 (e.g., specifically tracing every move of a tip of the surgical tool-bit 132) using the sensors in the flexible joint members 150, 170, data about the location of the working arm 140 (and the surgical tool-bit 132) is generated and stored in the computer 121 or another computer and/or memory device. The computer 121 can execute and/or run three-dimensional modeling software (e.g., that is the same as the dental surgical planning software program described elsewhere herein or a different software program) that is programmed to create a modified or post-operative virtual three-dimensional model 326 (FIG. 9) of at least a portion of the mouth 12 of the patient 10. The post-operative virtual three-dimensional model 326 is based on (i) the pre-operative three-dimensional virtual model 325 (FIG. 1) of the mouth 12 and (ii) the data collected regarding the positions of the working arm 140 during the procedure. Specifically, the three-dimensional modeling software is designed to take the pre-operative three-dimensional virtual model 325 of the mouth 12 of the patient 10 and to modify the pre-operative three-dimensional virtual model 325 based on the procedure conducted using the robotic system 100. As such, the post-operative three-dimensional virtual model 326 of the at least a portion of the virtual mouth 12' includes

the virtual teeth 14', the virtual soft tissue 18', the virtual surgical site 20', the virtual rigid grounding member 200', and in some implementations that took a CT scan (e.g., a dental CBCT scan), virtual bone 16' (e.g., jawbone), which are in the pre-operative three-dimensional virtual model 325. However, depending on the procedure and the data collected during the same, the post-operative three-dimensional virtual model 326 also includes modifications at the surgical site 20'.

For example, as shown in FIG. 9, if the operator 400 creates an osteotomy using a surgical drill-bit tool 132 while the robotic system 100 tracked the procedure, the tracking of the positions of the working arm 140 produces data indicative of the location of the surgical drill-bit tool 132 used during the procedure relative to the soft tissue 18 and jawbone 16 in the mouth 12 of the patient 10 relative to the rigid grounding member 200 (and thus the established origin, O). As such, the three-dimensional modeling software is able to identify how the surgical drill-bit tool or tools 132 interfered with the pre-operative three-dimensional virtual model 325 and update the pre-operative three-dimensional virtual model 325 by removing portions thereof based on the interference to result in the post-operative three-dimensional virtual model 326 including a virtual opening or socket 25' in the soft tissue 18' and/or in the bone 16'. That is, the interference of the surgical drill-bit tool or tools 132 indicates that the surgical drill-bit tool or tools 132 were used to drill and/or remove material resulting in the illustrated virtual opening or socket 25'. As such, the three-dimensional modeling software is able to modify the pre-operative three-dimensional virtual model 325 by removing the material that corresponds to the material that was actually removed from the mouth 12 of the patient 10 during the procedure. The result is the modified or post-operative three-dimensional virtual model 326 of the mouth 12 of the patient 10, which depicts the post-operative situation in the mouth 12 of the patient 10 (e.g., with the removed soft tissue and/or jawbone material). Thus, it is not necessary for the operator 400 to take a post-operative scan of the mouth 12 of the patient 10 to acquire the post-operative patient situation. The patient 10 is spared this extra scanning step.

Further, for another example, as shown in FIG. 9, if the operator 400 placed a dental implant using an implant driving tool 132 while the robotic system 100 tracked the procedure, the tracking of the positions of the working arm 140 produces data indicative of the location of the implant driving tool (and thus the position of the dental implant coupled thereto) relative to the rigid grounding member 200 (and thus the established origin, O). As such, the three-dimensional modeling software is able to identify how the implant driving tool (and the dental implant coupled thereto) interfered with and/or moved relative to the pre-operative three-dimensional virtual model 325 and update the pre-operative three-dimensional virtual model 325 based on the interference to result in the post-operative three-dimensional virtual model 326 including a virtual dental implant 30' placed in the virtual opening or socket 25' at a location and orientation that corresponds with the placement and orientation of the actual dental implant installed in the mouth 12 of the patient 10 using the robotic system 100. Thus, it is not necessary for the operator 400 to take a post-operative scan of the mouth 12 of the patient 10 to acquire the post-operative patient situation including the location and orientation of the dental implant installed therein. The patient 10 is spared this extra scanning step.

The tracking/monitoring of the position of the working arm 140 and/or grounding arm 160 during a semi-manual

and/or manual procedure conducted using the robotic system **100** can be used to create a variety of modified or post-operative virtual three-dimensional models of at least a portion of the mouth **12** of the patient **10** in addition to the ones described herein and shown in FIG. **9**. For example, modified or post-operative virtual three-dimensional models can be automatically generated by, for example, the computer **121** running the three-dimensional modeling software after a conventional dentistry tooth-prep is performed using the robotic system, after a temporary prosthesis is shaped using the robotic system **100**, after a denture is modified using the robotic system **100**, etc. Various other manual/semi-manual procedures, such as the procedures described elsewhere herein, can be tracked/monitored as described above for generating positional data for use in generating modified or post-operative virtual three-dimensional models, thereby avoiding post-operative scans (e.g., post-operative intraoral surface scans, post-operative dental CBCT scan, etc.).

Exemplary Uses of the Robotic System **100**

The robotic system **100** of the present disclosure can be used to conduct a variety of procedures automatically, manually, or a combination thereof. One example of a procedure performable by the robotic system **100** is the creating of an osteotomy. The creating of the osteotomy is performed using one or more surgical drill-bit tools **132** coupled to the robotic system **100** to form a socket and/or opening in a jawbone **16** of a patient **10** that is suitable for receiving a dental implant therein. Additionally, in some implementations, the performing of the osteotomy also uses one or more surgical tapping tools **132** coupled to the robotic system **100** to form threads in the previously formed socket/opening in the jawbone **16** of the patient **10** that is suitable for receiving the dental implant therein. A second example of a procedure performable by the robotic system **100** is the installing of a dental implant. The installing of the dental implant is performed using an implant driving tool **132** coupled to the robotic system **100** to install the dental implant in an opening in a jawbone **16** of a patient **10**. A third example of a procedure performable by the robotic system **100** is the performing of an alveolectomy. The alveolectomy is performed using a bone shaving/removal tool **132** coupled to the robotic system **100** to removal bone material from a jawbone **16** of a patient **10**. A fourth example of a procedure performable by the robotic system **100** is the performing of an alveoloplasty. The alveoloplasty is performed using a surgical bone contouring tool **132** coupled to the robotic system **100** to contour a portion of a jawbone **16** of a patient **10**. A fifth example of a procedure performable by the robotic system **100** is the developing of a tooth-crown-prep. The development of a tooth-crown-prep is performed using one or more surgical dental drill-bit tools **132** and/or dental shaver tool-bits **132** to remove portions of a tooth (e.g., occlusal portions) such that the tooth is suitable for receiving a custom crown thereon. A sixth example of a procedure performable by the robotic system **100** is the modifying of a denture for use as part of a hybrid prosthesis. A hybrid prosthesis includes a modified denture bonded with one or more abutments or cylinders. Typically, the modified denture is coupled to the dental implants via the one or more abutments or cylinders, which attach to respective ones of the dental implants. The robotic system **100** can be used to aid in the creation of the modified denture by precisely drilling holes in the denture in locations that directly correspond with central axes of the dental implants installed in the mouth of a patient **10**, which were installed using the robotic system **100**. As such, when the one or more abutments or

cylinders are attached to the dental implants, the drilled holes in the denture match up with (i.e., are aligned with) the abutments or cylinders and can be bonded thereto to create the hybrid prosthesis. A seventh example of a procedure performable by the robotic system **100** is the creating of a provisional restoration. The creating of the provisional restoration is performed using one or more shaver and/or sculpting tool-bits **132** to remove portions of a tooth blank such that the tooth blank is sculpted to have an anatomical tooth shape for attachment to an installed dental implant.

It is contemplated that any of the above seven examples and any of the following disclosed implementations, can be performed automatically by the robotic system **100** loaded with a surgical plan with no or little input from an operator (e.g., except for selecting of a start procedure button), or performed manually and/or semi-manually by an operator **400** that manually manipulates the working arm **140** of the robotic system **100** that is either constrained by or free from an invisible barrier wall/area **450**. It is further contemplated that any element and/or step from any of the following implementations can be removed and/or replaced with any other disclosed element in any of the other disclosed implementations.

According to a first implementation of the disclosed concepts of the present disclosure, the robotic system **100** is used to install a dental implant in the mouth **12** of the patient **10**. The robotic system **100** includes the base **120**, the grounding arm **160**, the working arm **140**, and one or more sensors. The grounding arm **160** has a first end **161a** and a second end **161b**. The first end **161a** of the grounding arm **160** is coupled to the base **120** and the second end **161b** of the grounding arm **160** is configured to be coupled to a fixed structure in the mouth **12** of the patient **10** for establishing the origin, O, for the robotic system **100** relative to the mouth **12** of the patient **10**. In such implementations, the second end **161b** of the grounding arm **160** has at least six degrees of freedom relative to the base **120**. The working arm **140** has a first end **141a** and a second end **141b**. The first end **141a** of the working arm **140** extends from the base **120** and the second end **141b** of the working arm **140** is configured to be coupled with one or more of the surgical tools **132** for use during installation of the dental implant in the mouth **12** of the patient **10**. A portion of the working arm **140** has at least six degrees of freedom relative to the base **120** and is moveable to (i) form an opening in the bone **16** within the mouth **12** of the patient **10** and (ii) install the dental implant in the formed opening. The one or more sensors (e.g., the sensors in the flexible joint members **150**, **170**) monitor the positions of the grounding arm **160** and the working arm **140** and generate positional data that is used to create a post-operative virtual three-dimensional implant level model (e.g., model **326** of FIG. **9**) of at least a portion of the mouth **12** of the patient **10**.

In the first implementation, the post-operative virtual three-dimensional implant level model is created without use of a scanning abutment coupled to the dental implant installed in the mouth **12** of the patient **10**. Further, the moveable portion of the working arm **140** is (i) manually-moveable by the operator **400** of the robotic system **100**, (ii) automatically moveable by one or more motors (e.g., motors in the flexible joint members **150**, **170**) of the robotic system **100**, or (iii) both. The fixed structure in the mouth **12** of the patient **10** is one or more teeth, jawbone, the rigid grounding member **200**, or any combination thereof.

According to a second implementation of the disclosed concepts of the present disclosure, a method of creating the post-operative virtual three-dimensional model **326** (FIG. **9**)

of at least a portion of the mouth **12** of the patient **10**, where the mouth **12** includes a dental implant installed using the robotic system **100** during a dental surgical procedure, includes attaching the rigid grounding member **200** to a fixed position within the mouth **12** of the patient **10**. The method also includes obtaining the pre-operative virtual three-dimensional model **325** (FIG. **1**) of the mouth **12** of the patient **10** with the rigid grounding member **200** therein. The method further includes, coupling the grounding arm **160** of the robotic system **100** to the rigid grounding member **200** in the mouth **12** of the patient **10**, thereby establishing the origin, O, (FIG. **8B**) for the mouth **12** of the patient **10**. The method also includes moving (e.g., automatically or manually, or a combination of both), as part of the dental surgical procedure, at least a portion of the working arm **140** of the robotic system **100** coupled to the dental-implant-driving tool **132** to install the dental implant in the mouth **12** of the patient **10**. The method also includes monitoring, during the dental surgical procedure, a position of the grounding arm **160** and the working arm **140** to generate positional data related to the location of the dental-implant-driving tool **132** relative to the established origin, O and creating the post-operative virtual three-dimensional model **326** (FIG. **9**) of the at least a portion of the mouth **12** of the patient **10** based on the obtained pre-operative virtual three-dimensional model **325** (FIG. **1**) and the generated positional data.

In the second implementation, the creating the post-operative virtual three-dimensional model **326** (FIG. **9**) occurs without use of a scanning abutment coupled to the installed dental implant. Further, the creating includes modifying the pre-operative virtual three-dimensional model **325** of the mouth **12** of the patient **10** to include at least a portion of a virtual model of the dental implant (e.g., virtual dental implant **30'** shown in FIG. **9**) installed in the mouth **12** of the patient **10**. In some versions of the second implementation, the method further includes prior to the moving, determining the invisible boundary wall/area **450** (FIGS. **8A** and **8B**) to be established around a pre-determined location (e.g., the surgical site **20** shown in FIGS. **6** and **7**) for the dental implant to be installed in the mouth **12** of the patient **10** and during the moving, automatically enforcing the determined invisible boundary wall/area **450** by preventing the working arm **140** of the robotic system **100** from being moved in a manner that would cause the dental implant to be installed outside of the determined invisible boundary wall/area **450**.

According to a third implementation of the disclosed concepts of the present disclosure, a method of automatically shaving alveolar bone in the mouth **12** of the patient **10** using the robotic system **100** includes attaching the rigid grounding member **200** to a fixed position (e.g., tooth **14a** shown in FIG. **6**) within the mouth **12** of the patient **10**. The method further includes obtaining a pre-shaved virtual model (e.g., the same as, or similar to, the pre-operative three-dimensional virtual model **325** shown in FIG. **1**) of the mouth **12** of the patient **10** with the rigid grounding member **200** therein. The method further includes coupling the grounding arm **160** of the robotic system **100** to the rigid grounding member **200** in the mouth **12** of the patient **10**, thereby establishing the origin, O, (FIG. **8B**) for the mouth **12** of the patient **10**. The method further includes developing a plan for automatically moving a bone-cutting tool **132** relative to the established origin, O, to shave a portion of the alveolar bone in the mouth **12** of the patient **10**. The method further includes attaching the bone-cutting tool **132** to the working arm **140** of the robotic system **100** and executing the developed plan by automatically moving the bone-cutting tool **132** via the working arm **140** of the robotic

system **100**, thereby shaving the alveolar bone in the mouth **12** of the patient **10** according to the developed plan such that an exposed ridge of the alveolar bone in the mouth **12** of the patient **10** is sufficiently widened for drilling and receiving a dental implant therein.

According to a fourth implementation of the disclosed concepts of the present disclosure, a method of installing a dental implant in the mouth **12** of the patient **10** using the robotic system **100** includes developing a plan for installing the dental implant in the mouth **12** of the patient **10**. The developed plan includes (i) a first sub-plan for shaving an exposed portion of bone in the mouth **12** with a first tool **132** (e.g., a surgical bone shaver), thereby creating a sufficiently widened portion of the bone for receiving the dental implant therein, (ii) a second sub-plan for forming an opening or socket in the sufficiently widened portion of the bone to receive the dental implant with a second tool **132** (e.g., a surgical drill-bit tool), and (iii) a third sub-plan for installing the dental implant within the opening with a third tool **132** (e.g., an implant driving tool). The method further includes establishing the origin, O, (FIG. **8B**) for the mouth **12** of the patient **10** by coupling the grounding arm **160** of the robotic system **100** to the rigid grounding member **200** in the mouth **12** of the patient **10**. Then the plan is executed by (1) coupling the first tool **132** to the working arm **140** of the robotic system **100** and shaving the exposed portion of the bone in the mouth **12** of the patient **10** by moving at least a portion of the working arm **140** (e.g., by moving the tool **155** shown in FIG. **2**) according to the first sub-plan, (2) coupling the second tool **132** to the working arm **140** of the robotic system **100** and forming the opening in the bone **16** (FIG. **7**) in the mouth **12** of the patient **10** by moving the at least a portion of the working arm **140** according to the second sub-plan, and (3) coupling the third tool **132** and the dental implant to the working arm **140** of the robotic system **100** and installing the dental implant into the opening in the bone **16** in the mouth **12** of the patient **10** by moving the at least a portion of the working arm **140** according to the third sub-plan.

In the fourth implementation, the method can further include monitoring, during the installing the dental implant, a position of the grounding arm **160** and the working arm **140** to generate positional data related to (i) the location of the dental implant relative to the established origin, O, (ii) the location of the third tool **132** relative to the established origin, O, or (iii) both (i) and (ii). Further, the method can further include creating a post-operative virtual three-dimensional model (e.g., the same as, or similar to, the modified or post-operative virtual three-dimensional model **326** shown in FIG. **9**) of at least a portion of the mouth **12** of the patient **10** based on the obtained pre-operative virtual model **325** and the generated positional data, where the at least a portion of the mouth **12** includes the dental implant. In the fourth implementation, the creating the post-operative virtual three-dimensional model occurs without use of a scanning abutment coupled to the installed dental implant.

According to a fifth implementation of the disclosed concepts of the present disclosure, a method of shaving alveolar bone in the mouth **12** of the patient **10** using the robotic system **100** includes establishing the origin, O, (FIG. **8B**) for the mouth **12** of the patient **10** by coupling the grounding arm **160** of the robotic system **100** to the rigid grounding member **200** in the mouth **12** of the patient **10**. The method further includes determining the invisible boundary wall/area **450** to be established around a pre-determined location (e.g., the surgical site **20** shown in FIGS. **6** and **7**) in the mouth **12** of the patient **10**. The method

further includes coupling a bone-cutting tool **132** to the working arm **140** of the robotic system **100** and moving (e.g., manually moving) at least a portion of the working arm **140** of the robotic system **100** to shave the alveolar bone in the mouth **12** of the patient **10**. During the moving, the method further includes automatically enforcing the determined invisible boundary wall/area **450** by preventing the working arm **140** of the robotic system **100** from being moved in a manner that would cause the bone-cutting tool **132** to be moved past the determined invisible boundary wall/area **450**. The method further includes monitoring, during the moving, a position of the grounding arm **160** and/or the working arm **140** to generate positional data related to the location of the bone-cutting tool **132** relative to the established origin, O.

According to a sixth implementation of the disclosed concepts of the present disclosure, a method of automatically preparing a tooth in the mouth **12** of the patient **10** to receive a custom crown using the robotic system **100** includes attaching the rigid grounding member **200** to a fixed position (e.g., tooth **14a** shown in FIG. **5**) within the mouth **12** of the patient **10** and obtaining a pre-shaped virtual three-dimensional model (e.g., the same as, or similar to, the pre-operative three-dimensional virtual model **325**) of the mouth **12** of the patient **10** with the rigid grounding member **200**. The method further includes coupling the grounding arm **160** of the robotic system **100** to the rigid grounding member **200** in the mouth **12** of the patient **10**, thereby establishing the origin, O, (FIG. **8B**) for the mouth **12** of the patient **10**. The method further includes developing a plan for automatically moving one or more tools **132** relative to the established origin, O, to shape the tooth in the mouth **12** of the patient **10** to receive the custom crown. In response to the working arm **140** of the robotic system **100** being coupled with at least one of the one or more tools **132**, the method further includes implementing the developed plan by automatically moving at least a portion of the working arm **140** (e.g., the tool **155** best shown in FIG. **2**) according to the developed plan, thereby shaping the tooth in the mouth **12** of the patient **10** such that the tooth is substantially shaped according to the developed plan.

In the sixth implementation, the method can further include designing the custom crown based on the developed plan, fabricating the designed custom crown using a fabrication machine, and attaching the fabricated custom crown to the prepared tooth.

According to a seventh implementation of the disclosed concepts of the present disclosure, a method of preparing a tooth in the mouth **12** of the patient **10** to receive a custom crown using the robotic system **100** includes attaching the rigid grounding member **200** to a fixed position (e.g., tooth **14a** shown in FIG. **5**) within the mouth **12** of the patient **10** and obtaining a pre-shaped virtual three-dimensional model (e.g., the same as, or similar to, the pre-operative three-dimensional virtual model **325**) of the mouth **12** of the patient **10** with the rigid grounding member **200** therein. The method further includes determining the invisible boundary wall/area **450** to be established around the tooth in the mouth **12** to be shaped. The method further includes coupling the grounding arm **160** of the robotic system **100** to the rigid grounding member **200** in the mouth **12** of the patient **10**, thereby establishing the origin, O, for the mouth **12** of the patient **10**. In response to the working arm **140** of the robotic system **100** being coupled with a shaping tool **132**, the method further includes manually moving at least a portion of the working arm **140** (e.g., the tool **155** best shown in FIG. **2**) to shape the tooth in the mouth **12** of the patient **10**. The

method further includes automatically enforcing the determined invisible boundary wall/area **450** by preventing the working arm **140** from being moved in a manner that would cause a cutting portion of the shaping tool **132** to move outside of the determined invisible boundary wall/area **450**. The method further includes monitoring, during the moving, a position of the grounding arm **160** and/or the working arm **140** to generate positional data related to the location of the cutting portion of the shaping tool **132** relative to the established origin, O. The method further includes creating a post-shaped virtual three-dimensional model (e.g., similar to the post-operative virtual three-dimensional model **326** shown in FIG. **9**) of at least a portion of the mouth **12** of the patient **10** based on the obtained pre-shaped virtual model and the generated positional data, wherein the at least a portion of the mouth **12** includes the shaped tooth.

In the seventh implementation, the creating the post-shaped virtual model occurs without scanning the mouth after the manually moving. Further, the determined invisible boundary wall/area **450** allows for the manual moving of the at least a portion of the working arm **140** to shape the tooth while maintaining a convergent axial wall angulation of the tooth and allowing manual up and down movements along a long axis of the tooth to allow creation of a crown margin that follows a gingival margin contour in the mouth **12** of the patient **10**. Further, the pre-shaped virtual three-dimensional model can be derived from scan data generated during a CT scan, scan data generated during an intraoral surface scan, scan data generated during a surface scan of an impression of at least a portion of the mouth of the patient, scan data generated during a surface scan of a physical model of at least a portion of the mouth **12** of the patient **10**, or any combination thereof.

According to an eighth implementation of the disclosed concepts of the present disclosure, a method of modifying a denture to be coupled with a plurality of dental implants in the mouth **12** of the patient **10** (e.g., via abutments or cylinders bonded to the modified denture) as a hybrid prosthesis using the robotic system **100** includes obtaining a first virtual model of the mouth **12** of the patient **10** with the denture therein. The method further includes removing the denture from the mouth **12** of the patient **10** and attaching a first rigid grounding member (e.g., the rigid grounding member **200**) to a fixed position (e.g., the tooth **14c** shown in FIG. **5**) within the mouth **12** of the patient **10**. The method further includes obtaining a second virtual model of the mouth **12** of the patient **10** with the first rigid grounding member therein and attaching a second rigid grounding member to the denture outside of the mouth **12** of the patient **10**. The method further includes obtaining a third virtual model of the denture with the second rigid grounding member attached thereto. The method further includes establishing the origin, O, (FIG. **8B**) for the mouth **12** of the patient **10** by coupling the grounding arm **160** of the robotic system **100** to the first rigid grounding member (e.g., the rigid grounding member **200**) in the mouth **12** of the patient **10**. The method further includes using the working arm **140** of the robotic system **100** coupled to a dental-implant-driving tool **132** to install the plurality of dental implants in the mouth **12** of the patient **10** and monitoring, during the installing, a position of the grounding arm **160** and/or the working arm **140** to generate positional data related to the location of the dental-implant-driving tool **132** relative to the established origin, O. The method further includes creating a fourth virtual model of at least a portion of the mouth **12** of the patient **10** based on the obtained second virtual model and the generated positional data. Based at least in part on

the first, the third, and the fourth virtual models, the method includes developing a plan for automatically modifying the denture such that the denture can be coupled with the installed plurality of dental implants (e.g., via a plurality of abutments or cylinders bonded to the modified denture that mate with the installed dental implants). The method further includes coupling the grounding arm **160** of the robotic system **100** to the second rigid grounding member attached to the denture. The method further includes using the working arm **140** of the robotic system **100**, coupled to a drill-bit tool **132**, to modify the denture by creating a plurality of holes therein. The holes are created in the denture at specific positions such that abutments or cylinders attached to the dental implants align with the holes such that the modified denture can be bonded to the abutments or cylinders and form the hybrid prosthesis. Additional details on hybrid prostheses, dentures, and the modification of dentures to be used in/as a hybrid prosthesis can be found in U.S. Published Patent Application No. 2014-0272797, which is hereby incorporated by reference herein in its entirety.

According to a ninth implementation of the disclosed concepts of the present disclosure, a method of manufacturing a patient specific temporary prosthesis (PSTP) for use in manufacturing a permanent prosthesis for attachment to a dental implant installed in a mouth of a patient includes establishing an origin for a PSTP blank by coupling the grounding arm **160** of the robotic system **100** to the PSTP blank via a fixture. The method further includes using the working arm **140** of the robotic system **100** coupled to a sculpting tool **132** to modify the PSTP blank such that the PSTP blank is transformed into the PSTP having a tooth-like shape suitable for attachment to the dental implant installed in the mouth **12** of the patient **10**. The method further includes monitoring, during the modifying, a position of the grounding arm **160** and/or the working arm **140** to generate positional data related to the location of the sculpting tool **132** relative to the established origin. Based at least in part on the generated positional data, the method further includes creating a virtual three-dimensional model of at least a portion of the PSTP and attaching the PSTP to the dental implant in the mouth **12** of the patient **10**. The method further includes permitting gingival tissue (e.g., soft tissue **18** shown in FIGS. **6** and **7**) surrounding the PSTP to heal in the mouth **12** of the patient **10**. In response to the healed gingival tissue surrounding the PSTP in the mouth **12** of the patient **10** satisfying a threshold, the method further include manufacturing the permanent prosthesis as a replica of the PSTP using the created virtual model. However, in response to the healed gingival tissue surrounding the PSTP in the mouth **12** of the patient **10** not satisfying the threshold, the method further includes (i) physically modifying the PSTP, (ii) scanning the modified PSTP to obtain a modified virtual model of at least a portion of the modified PSTP, and (iii) manufacturing the permanent prosthesis as a replica of the modified PSTP using the obtained modified virtual model. Additional details on PSTPs, fixtures, and the use of PSTPs for creating and/or designing permanent components can be found in U.S. Published Patent Application Nos. 2014-0080095 and 2014-0080092, which are both hereby incorporated by reference herein in their entireties.

According to a tenth implementation of the disclosed concepts of the present disclosure, the robotic system **100** is used to section (e.g., remove and/or cut) soft tissue (e.g., gingival tissue) in the mouth **12** of the patient **10**. The sectioning involves the coupling of a cutting tool **132** (e.g., scalpel tool) to the working arm **140** of the robotic system

100. Using the robotic system to automatically section the soft tissue **18** can be result in soft tissue modification that is more predictable and/or more reliable than free-handing an incision using, for example, a tissue punch or a freehand scalpel. Further, the use of the robotic system **100** coupled to a scalpel tool **132** to section soft tissue can result in accelerated and/or more aesthetic healing of the soft tissue as compared to free-handing an incision. In some implementations, the soft tissue can be carved out using the robotic system **100** to create a location to place a dental implant. In some implementations, soft tissue can be carved out using the robotic system **100** for use in other areas in the mouth (e.g., for use in a tissue graft).

According to an eleventh implementation of the disclosed concepts of the present disclosure, after registering the robotic system **100** to a mouth of a patient using a rigid grounding member as described herein, the robotic system **100** is used to track the location of drilled sockets/openings (e.g., during the creation of an osteotomy) in the jawbone **16** (FIG. **5**) that are then filled with idealized bone grafting materials. The grafting materials are allowed to osseointegrate with the jawbone material and the patient is allowed to heal (e.g., for six months). After a sufficient amount of healing has occurred, the patient can return for the installation of dental implants at the locations of the grafting materials. The robotic system **100** is then reregistered to the mouth of the patient by, for example, reattaching a rigid grounding member to the mouth of the patient in the same exact location as previously installed. Alternatively, the rigid grounding member is left in the mouth of the patient during the healing phase. In such an alternative implementation, the rigid grounding member may have a size and shape such that the rigid grounding member does not interfere with the patient's mastication function. For example, such a rigid grounding member may be a surgical screw that partially protrudes from a jawbone of the patient in a manner that does not significantly impact the patient's mastication functions. As the robotic system **100** was used to create the sockets/openings that were filled with the grafting materials, the robotic system **100** knows the locations of the idealized bone grafting materials (e.g., by tracking the movements of the working arm **140** during the original drilling relative to an established origin in the mouth of the patient) and can be preprogrammed to automatically drill the location of the idealized bone grafting materials to place the dental implants therein. As it is desirable to install the dental implants into the idealized bone graft materials and not the relatively soft jawbone material therearound, this eleventh implementation aids the operator in placement of the dental implants without having to take a CT scan of the mouth of the patient after the bone grafts are performed.

Portions of the present disclosure describe that a post-operative virtual model of a portion of a mouth of a patient can be created without taking a post-operative scan of the mouth of the patient. However, in some alternative implementations, a post-operative intraoral surface scan can be taken without a scan member (e.g., scannable healing abutment, scan cap, etc.) attached to an installed implant to capture soft tissue information. This surface scan can be merged with a pre-operative CT scan of the mouth of the patient as modified by data obtained the tracing of the procedure as described herein to create a post-operative virtual model. That is, the post-operative virtual models described herein can further be modified by merging with a port-operative intraoral surface scan to, for example, improve the accuracy of the soft tissue in the post-operative virtual model. Additional details on creating a virtual model

with bone/hard tissue information and soft tissue information can be found in U.S. Pat. No. 8,651,858, which is hereby incorporated by reference herein in its entirety.

Portions of the present disclosure describe using the robotic system **100** to shave or sculpt portions of a jawbone **16** in the mouth **12** of the patient **10**. It is important to note that such sculpting occurs in three dimensions as the bone can be removed in an X-Y plane and/or in the Z-axis direction. A non-limiting example of when bone may be removed is to remove a narrow ridge of bone where it is desired to place a dental implant. The removing of such bone will result in a wider ridge (e.g., an adequate amount of restorative space) that is better for drilling to receive the dental implant as compared to a narrow ridge. Further, the shaving or sculpting of bone can be used to manipulate a vertical dimension of occlusion (VDO) in the mouth **12** of the patient **10** to provide an adequate amount of restorative space in light of the stack up height of the designed/desired restorative components (e.g., dental implant, abutment, crown, etc.) that will be installed in the mouth of the patient. Thus, in some implementations, the robotic system **100** is used to shave bone (e.g., alveolar ridge bone) such that the VDO is manipulated such that the installed components (e.g., dental implant, abutment, crown, etc.) fit properly within the mouth **12** of the patient **10**. Specifically, such that the occlusal surface of the installed crown mates with the occlusal surface of the opposing tooth/teeth in the mouth **12** of the patient **10**.

Portions of the present disclosure describe various surgical tools **132**. In addition to the described tools **132**, various other tools **132** can be coupled with the working arm **140** of the robotic system **100** and used in the same, or similar, fashion as described herein. For example, a probe tool **132** (e.g., a tool with a metal ball or hook) can be coupled to the working arm **140** for use in checking for pockets between teeth and gingival tissue. The robotic system **100** can use the probe tool **132** to determine a length and/or depth of such pockets. Further, the probe tool **132** can be used as a mechanical sensing probe to find the location of structures (e.g., the rigid grounding member **200**, teeth, gingival tissue, palate, etc.) in the mouth **12** of the patient **10**. Such a use of the robotic system **100** can be used when, for example, an oral surgeon performs a manual procedure without using the working arm **140** of the robotic system **100** and then wants to use the robotic system **100** to digitally capture any modifications made to the mouth **12** of the patient **10**. In such a scenario, the operator (e.g., oral surgeon) can use the robotic system **100** with a mechanical sensing probe coupled to the working arm **140** to sense any changes in the mouth **12**. Further, the mechanical sensing can be used to determine hard structures in the mouth **12** like teeth and bone and/or the mechanical sensing can be used to determine soft tissue contours and/or depths of soft tissue at a particular site.

Portions of the present disclosure describe using the robotic system **100** to create an osteotomy in the jawbone **16** of the patient **10**. It is important to note that the surgical plan implemented by the robotic system **100** to perform an osteotomy procedure is based, at least in part, on information regarding the quality (e.g., density) of the jawbone **16** in the patient **10** at the surgical site **20**, which is typically derived from a CT scan (e.g., a dental CBCT scan) and/or an X-ray scan. This determination can be performed automatically by the dental surgical planning software program and/or manually by an operator and inputted into the dental surgical planning software program. The bone quality at a surgical site **20** is typically categorized as one or more of four types of bone including Type I, Type II, Type III, or

Type IV bone, where Type I is the most dense and Type IV is the least dense. Thus, in a patient **10** determined to need a dental implant in a surgical site **20** having Type I bone, the surgical plan may include instructions for the robotic system **100** to create a right-size socket/opening in the jawbone **16** and then to tap the socket/opening with a surgical tapping tool **132**. By right-size socket/opening it is meant that the diameter of the created socket/opening and/or of the final drill-bit tool **132** used to create the osteotomy is about equal to a minor diameter of the dental implant to be installed therein. For another example, in a patient **10** determined to need a dental implant in a surgical site **20** having Type IV bone, the surgical plan may include instructions for the robotic system **100** to create an under-size socket/opening in the jawbone **16** without tapping the socket/opening. By under-size socket/opening it is meant that the diameter of the created socket/opening and/or of the final drill-bit tool **132** used to create the osteotomy is smaller than a minor diameter of the dental implant to be installed therein.

In some implementations, the robotic system **100** includes one or more sensors that generate data during the performance of a desired procedure (e.g., osteotomy) that is used in modifying/updating the surgical plan in real-time (e.g., after the procedure is already underway—has already started to be implemented). The sensors can include the sensors described elsewhere herein (e.g., the sensors in the flexible joint member **150** coupled to the rigid arm members **145**), one or more torque sensors coupled to the tool **155**, one or more force sensors coupled to the tool **155**, one or more speed sensors coupled to the tool **155**, etc. When performing a surgical plan for an osteotomy, the robotic system **100** initially uses a first surgical drill-bit tool **132** having a first diameter to start the socket/opening in the jawbone **16**. The robotic system **100**, as it drills the jawbone **16** with the first surgical drill-bit tool **132**, monitors the data generated by the sensors to determine if the jawbone **16** is more or less dense than initially determined. Based on the data and/or the determination during the procedure (e.g., during the drilling using the first surgical drill-bit tool **132**), the surgical plan can be automatically modified/updated in real-time by the robotic system **100** and/or an operator can be prompted to permit a suggested modification. For example, if the robotic system **100** determines that the data from the sensors (e.g., torque sensors, force sensors, etc.) indicates that the required torque to spin the first surgical drill-bit tool **132** at the planned rate (e.g., 2000 RPMs) and/or the required force to advance the first surgical drill-bit tool **132** into the jawbone **16** is less than anticipated (e.g., based on the previously determined Type I bone), the robotic system **100** may alter or propose to alter the surgical plan because the actual dental situation appears to be different than initially determined. That is, the required less than anticipated torque/force indicates that the jawbone **16** being drilled is not Type I bone, but rather, type II bone. In such a situation, the surgical plan can be changed by, for example, not tapping the created socket/opening and/or by changing the final surgical drill-bit tool **132** to create an under-sized socket/opening as opposed to a right-sized socket/opening as originally planned for the Type I jawbone. The modification of the surgical plan can also include a change in the number of stepped surgical drill-bit tools **132** used in the creation of the osteotomy. For example, if the original surgical plan instructions called for three separate stepped surgical drill-bit tools **132** to be used for drilling Type IV bone, and during the procedure the robotic system **100** determines that the patient actually has Type II bone (e.g., based on the data from the torque and force sensors, etc.), the surgical system **100** can automati-

cally on the fly in real-time modify/update the surgical plan to add a fourth intermediate surgical drill-bit tool **132**. Various other modifications can be made to the surgical plan based on the monitored data from the torque and force sensors and/or other sensors. In summary, the robotic system **100** can modify/update a preplanned surgical plan based on real-time data with or without operator input. Examples of such modifications include (1) changing a preplanned amount of torque (e.g., applied to a surgical drill-bit tool, a surgical tapping tool, etc.) to be used by the robotic system when executing the developed plan; (2) changing a preplanned rotational speed (e.g., applied to a surgical drill-bit tool, a surgical tapping tool, etc.) to be used by the robotic system when executing the developed plan; (3) changing a preplanned amount of force (e.g., applied to a surgical drill-bit tool, a surgical tapping tool, etc.) to be used by the robotic system when executing the developed plan; (4) changing a preplanned number of the plurality of surgical tools (e.g., four surgical drill-bit tools instead of two surgical drill-bit tools) to be used by the robotic system when executing the developed plan. Such modifications are intended to increase the relative initial stability (e.g., resistance to motion from mastication forces) in installed dental implants, and this may promote increased reliability and overall survivability for the dental implants and the implant-borne prostheses.

While the present disclosure has been described with reference to one or more particular embodiments and implementations, those skilled in the art will recognize that many changes may be made thereto without departing from the spirit and scope of the present disclosure. Each of these embodiments and implementations and obvious variations thereof is contemplated as falling within the spirit and scope of the present invention, which is set forth in the claims that follow.

Alternative Implementations

Implementation 1. A robotic system for use during a dental surgical procedure including installation of a dental implant in a mouth of a patient, the robotic system comprising: a base; a grounding arm having a first end and a second end, the first end of the grounding arm being coupled to the base, the second end of the grounding arm being configured to be coupled to a fixed structure within the mouth of the patient for establishing an origin for the robotic system relative to the mouth of the patient, the second end of the grounding arm having at least six degrees of freedom relative to the base; a working arm having a first end and a second end, the first end of the working arm extending from the base, the second end of the working arm being configured to be coupled with one or more tools for use during the dental surgical procedure, a portion of the working arm having at least six degrees of freedom relative to the base and being moveable to (i) form an opening in bone within the mouth of the patient and (ii) install the dental implant in the formed opening; and one or more sensors to monitor positions of the grounding arm and the working arm, the one or more sensors generating positional data that is used to create a post-operative virtual three-dimensional implant level model of at least a portion of the mouth of the patient.

Implementation 2. The robotic system of implementation 1, wherein the post-operative virtual three-dimensional implant level model is created without use of a scanning abutment coupled to the dental implant installed in the mouth of the patient.

Implementation 3. The robotic system of implementation 1, wherein the generated positional data is used to modify a pre-operative virtual model of the mouth of the patient to

include at least a portion of a virtual three-dimensional model of a dental implant installed in the mouth of the patient during the dental surgical procedure.

Implementation 4. The robotic system of implementation 1, wherein the one or more tools include a drill-bit tool, a dental-implant-driving tool, a rotating mill tool, a saw tool, a probe tool, a scalpel tool, or any combination thereof.

Implementation 5. The robotic system of implementation 1, wherein the one or more sensors are electrically coupled to one or more processors of the robotic system and physically mounted to the grounding arm, the working arm, or both.

Implementation 6. The robotic system of implementation 1, wherein the moveable portion of the working arm is (i) manually-movable by an operator of the robotic system, (ii) automatically moveable by one or more motors of the robotic system, or (iii) both.

Implementation 7. The robotic system of implementation 1, wherein the fixed structure within the mouth of the patient is one or more teeth, jaw bone, or both.

Implementation 8. A robotic system for use during installation of a dental implant in a mouth of a patient, the robotic system comprising: a base; a grounding arm extending from the base and being configured to be coupled to a fixed structure within the mouth of the patient for establishing an origin for the robotic system relative to the mouth of the patient; a working arm extending from the base and being configured to be coupled with one or more tools for use during the installation of the dental implant, at least a portion of the working arm being movable to install the dental implant in the mouth of the patient; and one or more sensors to monitor positions of the grounding arm and the working arm, the one or more sensors generating positional data that is used to create a virtual model of at least a portion of the mouth of the patient.

Implementation 9. The robotic system of implementation 8, wherein the virtual model is created without use of a scanning abutment coupled to the dental implant installed in the mouth of the patient.

Implementation 10. The robotic system of implementation 8, wherein the generated positional data is used by one or more processors to modify a virtual model of the mouth of the patient to include at least a portion of a virtual model of the installed dental implant.

Implementation 11. The robotic system of implementation 8, wherein in response to the working arm being coupled with a drill-bit tool, the at least a portion of the working arm is further moveable to form an opening in bone within the mouth of the patient to receive the dental implant therein.

Implementation 12. The robotic system of implementation 8, wherein one or more processors of the robotic system are configured to control movement of the working arm to automatically install the dental implant in the mouth of the patient according to a pre-planned installation procedure, wherein the working arm is coupled to a dental-implant-driving tool during the automatic installation.

Implementation 13. The robotic system of implementation 12, wherein at least one of the one or more processors is configured to control movement of the working arm to automatically remove a portion of a jaw bone of the patient, thereby forming a socket for receiving the dental implant, according to the pre-planned installation procedure, wherein the working arm is coupled to a drill-bit tool during the removal.

Implementation 14. The robotic system of implementation 8, wherein a tip of the grounding arm has at least six degrees of freedom relative to the base and wherein a tip of

the one or more tools coupled to the working arm has at least six degrees of freedom relative to the base.

Implementation 15. The robotic system of implementation 8, wherein the at least a portion of the working arm is automatically moveable by one or more processors of the robotic system.

Implementation 16. The robotic system of implementation 8, wherein the one or more tools include a drill-bit tool, a dental-implant-driving tool, a rotating mill tool, a saw tool, a probe tool, a scalpel tool, or any combination thereof.

Implementation 17. A method of creating a post-operative virtual model of at least a portion of a mouth of a patient, the mouth including a dental implant installed using a robotic system during a dental surgical procedure, the method comprising: attaching a rigid grounding member to a fixed position within the mouth of the patient; obtaining a pre-operative virtual model of the mouth of the patient with the rigid grounding member therein; coupling a grounding arm of the robotic system to the rigid grounding member in the mouth of the patient, thereby establishing an origin for the mouth of the patient; moving, as part of the dental surgical procedure, at least a portion of a working arm of the robotic system coupled to a dental-implant-driving tool to install the dental implant in the mouth of the patient; monitoring, during the dental surgical procedure, a position of the grounding arm and the working arm to generate positional data related to the location of the dental-implant-driving tool relative to the established origin; and creating the post-operative virtual model of the at least a portion of the mouth of the patient based on the obtained pre-operative virtual model and the generated positional data.

Implementation 18. The method of implementation 17, wherein the creating the post-operative virtual model occurs without use of a scanning abutment coupled to the installed dental implant.

Implementation 19. The robotic system of implementation 17, wherein the creating includes modifying the pre-operative virtual model of the mouth of the patient to include at least a portion of a virtual model of the dental implant installed in the mouth of the patient.

Implementation 20. The method of implementation 17, wherein the working arm is coupled to the grounding arm.

Implementation 21. The method of implementation 17, wherein the working arm and the grounding arm are both electronically coupled to one or more processors of the robotic system.

Implementation 22. The method of implementation 17, further comprising: prior to the moving, determining an invisible boundary wall to be established around a pre-determined location for the dental implant to be installed in the mouth of the patient; and during the moving, automatically enforcing the determined invisible boundary wall by preventing the working arm of the robotic system to be moved in a manner that would cause the dental implant to be installed outside of the determined invisible boundary wall.

Implementation 23. A method of automatically shaving alveolar bone in a mouth of a patient using a robotic system, the method comprising: attaching a rigid grounding member to a fixed position within the mouth of the patient; obtaining a pre-shaved virtual model of the mouth of the patient with the rigid grounding member therein; coupling a grounding arm of the robotic system to the rigid grounding member in the mouth of the patient, thereby establishing an origin for the mouth of the patient; developing a plan for automatically moving a bone-cutting tool relative to the established origin to shave a portion of the alveolar bone in the mouth of the patient; attaching the bone-cutting tool to a working arm of

the robotic system; and executing the developed plan by automatically moving the bone-cutting tool via the working arm of the robotic system, thereby shaving the alveolar bone in the mouth of the patient according to the developed plan such that an exposed ridge of the alveolar bone in the mouth of the patient is sufficiently widened for drilling and receiving a dental implant therein.

Implementation 24. A method of installing a dental implant in a mouth of a patient using a robotic system, the method comprising: developing a plan for installing the dental implant in the mouth of the patient, the developed plan including (i) a first sub-plan for shaving an exposed portion of bone in the mouth with a first tool, thereby creating a sufficiently widened portion of the bone for receiving the dental implant therein, (ii) a second sub-plan for forming an opening in the sufficiently widened portion of the bone to receive the dental implant with a second tool, and (iii) a third sub-plan for installing the dental implant within the opening with a third tool; establishing an origin for the mouth of the patient by coupling a grounding arm of the robotic system to a rigid grounding member in the mouth of the patient; and executing the plan by: coupling the first tool to a working arm of the robotic system and shaving the exposed portion of the bone in the mouth of the patient by moving at least a portion of the working arm according to the first sub-plan; coupling the second tool to the working arm of the robotic system and forming the opening in the bone in the mouth of the patient by moving the at least a portion of the working arm according to the second sub-plan; and coupling the third tool and the dental implant to the working arm of the robotic system and installing the dental implant into the opening in the bone in the mouth of the patient by moving the at least a portion of the working arm according to the third sub-plan.

Implementation 25. The method of implementation 24, further comprising monitoring, during the installing the dental implant, a position of the grounding arm and the working arm to generate positional data related to (i) the location of the dental implant relative to the established origin, (ii) the location of the third tool relative to the established origin, or (iii) both (i) and (ii).

Implementation 26. The method of implementation 25, further comprising creating a post-operative virtual model of at least a portion of the mouth of the patient based on the obtained pre-operative virtual model and the generated positional data, the at least a portion of the mouth including the dental implant.

Implementation 27. The method of implementation 26, wherein the creating the post-operative virtual model occurs without use of a scanning abutment coupled to the installed dental implant.

Implementation 28. The method of implementation 26, wherein the creating includes modifying the pre-operative virtual model of the mouth of the patient to include at least a portion of a virtual model of the dental implant installed in the mouth of the patient.

Implementation 29. The method of implementation 24, wherein the coupling of the first tool, the second tool, and the third tool are automatically performed by the robotic system without intervention by an operator.

Implementation 30. The method of implementation 24, wherein the shaving, the forming, and the installing are automatically performed by the robotic system without intervention by an operator.

Implementation 31. The method of implementation 24, wherein one or more of (i) the moving the at least a portion of the working arm according to the first sub-plan, (ii) the

moving the at least a portion of the working arm according to the second sub-plan, and (iii) the moving the at least a portion of the working arm according to the third sub-plan involves manually moving the at least a portion of the working arm.

Implementation 32. The method of implementation 24, further comprising prior to the developing: attaching the rigid grounding member to a fixed position within the mouth of the patient; and obtaining a pre-operative virtual model of the mouth of the patient with the rigid grounding member therein.

Implementation 33. A method of shaving alveolar bone in a mouth of a patient using a robotic system, the method comprising: establishing an origin for the mouth of the patient by coupling a grounding arm of the robotic system to a rigid grounding member in the mouth of the patient; determining an invisible boundary wall to be established around a pre-determined location in the mouth of the patient; coupling a bone-cutting tool to a working arm of the robotic system; moving at least a portion of the working arm of the robotic system to shave the alveolar bone in the mouth of the patient; during the moving, automatically enforcing the determined invisible boundary wall by preventing the working arm of the robotic system from being moved in a manner that would cause the bone-cutting tool to be moved past the determined invisible boundary wall; and monitoring, during the moving, a position of the grounding arm and the working arm to generate positional data related to the location of the bone-cutting tool relative to the established origin.

Implementation 34. The method of implementation 33, further comprising creating a virtual model of at least a portion of the mouth of the patient based on the generated positional data.

Implementation 35. The method of implementation 33, wherein the alveolar bone is shaved such that an exposed ridge of the alveolar bone in the mouth of the patient is sufficiently widened for drilling and receiving a dental implant therein.

Implementation 36. The method of implementation 33, further comprising attaching the rigid grounding member to a fixed position within the mouth of the patient.

Implementation 37. The method of implementation 33, further comprising receiving a first virtual model of the mouth of the patient with the rigid grounding member therein.

Implementation 38. A method of automatically preparing a tooth in a mouth of a patient to receive a custom crown using a robotic system, the method comprising: attaching a rigid grounding member to a fixed position within the mouth of the patient; obtaining a pre-shaped virtual model of the mouth of the patient with the rigid grounding member therein; coupling a grounding arm of the robotic system to the rigid grounding member in the mouth of the patient, thereby establishing an origin for the mouth of the patient; developing a plan for automatically moving one or more tools relative to the established origin to shape the tooth in the mouth of the patient to receive the custom crown; and in response to a working arm of the robotic system being coupled with at least one of the one or more tools, implementing the developed plan by automatically moving at least a portion of the working arm according to the developed plan, thereby shaping the tooth in the mouth of the patient such that the tooth is substantially shaped according to the developed plan.

Implementation 39. The method of implementation 38, further comprising designing the custom crown based on the developed plan.

Implementation 40. The method of implementation 39, further comprising fabricating the designed custom crown using a fabrication machine.

Implementation 41. The method of implementation 40, further comprising attaching the fabricated custom crown to the prepared tooth.

Implementation 42. The method of implementation 39, wherein the designing occurs prior to the implementing.

Implementation 43. The method of implementation 38, further comprising, monitoring, during the implementing, a position of the grounding arm and the working arm to generate positional data related to the location of the at least one of the one or more tools relative to the established origin.

Implementation 44. The method of implementation 43, further comprising creating a post-shaped virtual model of at least a portion of the mouth of the patient based on the obtained pre-shaped virtual model and the generated positional data, the at least a portion of the mouth including the shaped tooth.

Implementation 45. The method of implementation 44, further comprising designing the custom crown based on the post-shaped virtual model of the at least a portion of the mouth of the patient.

Implementation 46. The method of implementation 45, further comprising fabricating the designed custom crown using a fabrication machine.

Implementation 47. The method of implementation 46, further comprising attaching the fabricated custom crown to the prepared tooth.

Implementation 48. The method of implementation 44, wherein the creating the post-shaped virtual model occurs without scanning the mouth after the implementing.

Implementation 49. A method of preparing a tooth in a mouth of a patient to receive a custom crown using a robotic system, the method comprising: attaching a rigid grounding member to a fixed position within the mouth of the patient; obtaining a pre-shaped virtual model of the mouth of the patient with the rigid grounding member therein; determining an invisible boundary wall to be established around the tooth in the mouth to be shaped; coupling a grounding arm of the robotic system to the rigid grounding member in the mouth of the patient, thereby establishing an origin for the mouth of the patient; in response to a working arm of the robotic system being coupled with a shaping tool, manually moving at least a portion of the working arm to shape the tooth in the mouth of the patient; automatically enforcing the determined invisible boundary wall by preventing the working arm from being moved in a manner that would cause a cutting portion of the shaping tool to move outside of the determined invisible boundary wall; monitoring, during the moving, a position of the grounding arm and the working arm to generate positional data related to the location of the cutting portion of the shaping tool relative to the established origin; and creating a post-shaped virtual model of at least a portion of the mouth of the patient based on the obtained pre-shaped virtual model and the generated positional data, the at least a portion of the mouth including the shaped tooth.

Implementation 50. The method of implementation 49, wherein the creating the post-shaped virtual model occurs without scanning the mouth after the manually moving.

Implementation 51. The method of implementation 49, wherein the determined invisible boundary wall allows for the manual moving of the at least a portion of the working arm to shape the tooth while maintaining a convergent axial wall angulation of the tooth and allowing manual up and down movements along a long axis of the tooth to allow

creation of a crown margin that follows a gingival margin contour in the mouth of the patient.

Implementation 52. The method of implementation 49, wherein the pre-shaped virtual model is derived from scan data generated during a dental CBCT scan, scan data generated during an intraoral surface scan, scan data generated during a surface scan of an impression of at least a portion of the mouth of the patient, scan data generated during a surface scan of a physical model of at least a portion of the mouth of the patient, or any combination thereof.

Implementation 53. A method of preparing a tooth in a mouth of a patient to receive a custom crown using a robotic system, the method comprising: coupling a grounding arm of the robotic system to the mouth of the patient, thereby establishing an origin for the mouth of the patient; in response to a working arm of the robotic system being coupled with a shaping tool, manually moving at least a portion of the working arm to shape the tooth in the mouth of the patient; monitoring, during the moving, a position of the grounding arm and the working arm to generate positional data related to the location of a cutting portion of the shaping tool relative to the established origin; and creating a post-shaped virtual model of at least a portion of the mouth of the patient based at least in part on the generated positional data.

Implementation 54. The method of implementation 53, wherein the creating the post-shaped virtual model occurs without scanning the mouth after the manually moving.

Implementation 55. The method of implementation 53, further comprising receiving a pre-shaped virtual model of the mouth of the patient with the rigid grounding member therein, the post-shaped virtual model of the at least a portion of the mouth of the patient further being based on the received pre-shaped virtual model of the mouth of the patient.

Implementation 56. A method of modifying a denture to be coupled with a plurality of dental implants in a mouth of a patient using a robotic system, the method comprising: attaching a first rigid grounding member to a fixed position within the mouth of the patient and attaching a second rigid grounding member to the denture; obtaining a pre-operative virtual model of the mouth of the patient with the first rigid grounding member and the denture therein; removing the denture, with the second rigid grounding member attached thereto, from the mouth of the patient; establishing an origin for the mouth of the patient by coupling a grounding arm of the robotic system to the first rigid grounding member in the mouth of the patient; using a working arm of the robotic system coupled to a dental-implant-driving tool, installing the plurality of dental implants in the mouth of the patient; monitoring, during the installing, a position of the grounding arm and the working arm to generate positional data related to the location of the dental-implant-driving tool relative to the established origin; creating a post-operative virtual model of at least a portion of the mouth of the patient based on the obtained pre-operative virtual model and the generated positional data; based at least in part on the post-operative virtual model, developing a plan for automatically modifying the denture such that the denture can be coupled with the installed plurality of dental implants; coupling the grounding arm of the robotic system to the second rigid grounding member attached to the denture; and using the working arm of the robotic system coupled to a drill-bit tool, modifying the denture by creating a plurality of holes therein such that each of the plurality of holes is aligned with a central axis of a corresponding one of the installed plurality of dental implants.

Implementation 57. The method of implementation 56, further comprising attaching a cylinder to each of the installed dental implants, the cylinders extending from the dental implants such that in response to the modified denture being positioned in the mouth of the patient, a portion of each cylinder protrudes through a respective one of the plurality of holes in the denture.

Implementation 58. The method of implementation 57, further comprising bonding the modified denture to the cylinders, thereby creating a hybrid prosthesis, wherein a diameter of each of the plurality of holes is sized such that each of the cylinders tightly fits in the respective one of the plurality of holes in response to the modified denture being installed in the mouth of the patient.

Implementation 59. A method of modifying a denture into a hybrid prosthesis using a robotic system, the method comprising: obtaining a pre-operative virtual model of the mouth of the patient with the denture therein; removing the denture from the mouth of the patient; installing a plurality of dental implants in the mouth of the patient using a first tool controlled by the robotic system; monitoring, during the installing, a position of the first tool to generate positional data; creating a post-operative virtual model of at least a portion of the mouth of the patient based on the obtained pre-operative virtual model and the generated positional data; and based at least in part on the post-operative virtual model, modifying the denture by creating a plurality of holes therein using a second tool controlled by the robotic system such that the denture can be coupled with the installed plurality of dental implants as the hybrid prosthesis.

Implementation 60. The method of implementation 59, wherein the first tool is a dental-implant-driving tool and wherein the second tool is a drill-bit tool.

Implementation 61. A method of modifying a denture to be coupled with a plurality of dental implants in a mouth of a patient as a hybrid prosthesis using a robotic system, the method comprising: obtaining a first virtual model of the mouth of the patient with the denture therein; removing the denture from the mouth of the patient; attaching a first rigid grounding member to a fixed position within the mouth of the patient; obtaining a second virtual model of the mouth of the patient with the first rigid grounding member therein; attaching a second rigid grounding member to the denture outside of the mouth of the patient; obtaining a third virtual model of the denture with the second rigid grounding member attached thereto; establishing an origin for the mouth of the patient by coupling a grounding arm of the robotic system to the first rigid grounding member in the mouth of the patient; using a working arm of the robotic system coupled to a dental-implant-driving tool, installing the plurality of dental implants in the mouth of the patient; monitoring, during the installing, a position of the grounding arm and the working arm to generate positional data related to the location of the dental-implant-driving tool relative to the established origin; creating a fourth virtual model of at least a portion of the mouth of the patient based on the obtained second virtual model and the generated positional data; based at least in part on the first, the third, and the fourth virtual models, developing a plan for automatically modifying the denture such that the denture can be coupled with the installed plurality of dental implants; coupling the grounding arm of the robotic system to the second rigid grounding member attached to the denture; and using the working arm of the robotic system coupled to a drill-bit tool, modifying the denture by creating a plurality of holes such that the denture can be coupled with the installed plurality of dental implants as the hybrid prosthesis.

Implementation 62. A method of manufacturing a patient specific temporary prosthesis (PSTP) for use in manufacturing a permanent prosthesis for attachment to a dental implant installed in a mouth of a patient, the method comprising: establishing an origin for a PSTP blank by coupling a grounding arm of a robotic system to the PSTP blank via a fixture; using a working arm of the robotic system coupled to a sculpting tool, modifying the PSTP blank such that the PSTP blank is transformed into the PSTP having a tooth-like shape suitable for attachment to the dental implant installed in the mouth of the patient; monitoring, during the modifying, a position of the grounding arm and the working arm to generate positional data related to the location of the sculpting tool relative to the established origin; and based at least in part on the generated positional data, creating a virtual model of at least a portion of the PSTP.

Implementation 63. The method of implementation 62, further comprising, designing the permanent prosthesis based at least in part on the created virtual model of the at least a portion of the PSTP.

Implementation 64. The method of implementation 62, wherein the fixture includes a non-rotational feature that couples with a corresponding non-rotational feature of the PSTP blank.

Implementation 65. A method of manufacturing a patient specific temporary prosthesis (PSTP) for use in manufacturing a permanent prosthesis for attachment to a dental implant installed in a mouth of a patient, the method comprising: establishing an origin for a PSTP blank by coupling a grounding arm of a robotic system to the PSTP blank via a fixture; using a working arm of the robotic system coupled to a sculpting tool, modifying the PSTP blank such that the PSTP blank is transformed into the PSTP having a tooth-like shape suitable for attachment to the dental implant installed in the mouth of the patient; monitoring, during the modifying, a position of the grounding arm and the working arm to generate positional data related to the location of the sculpting tool relative to the established origin; based at least in part on the generated positional data, creating a virtual model of at least a portion of the PSTP; attaching the PSTP to the dental implant in the mouth of the patient; permitting gingival tissue surrounding the PSTP to heal in the mouth of the patient; in response to the healed gingival tissue surrounding the PSTP in the mouth of the patient satisfying a threshold, manufacturing the permanent prosthesis as a replica of the PSTP using the created virtual model; in response to the healed gingival tissue surrounding the PSTP in the mouth of the patient not satisfying the threshold: (i) physically modifying the PSTP; (ii) scanning the modified PSTP to obtain a modified virtual model of at least a portion of the modified PSTP; and (iii)

manufacturing the permanent prosthesis as a replica of the modified PSTP using the obtained modified virtual model.

Implementation 66. A method of using a robotic system to automatically create a socket in a jawbone of a patient for receiving a dental implant therein, the method comprising: attaching a rigid grounding member to a fixed position within the mouth of the patient; obtaining a pre-operative virtual model of the mouth of the patient with the rigid grounding member therein; coupling a grounding arm of the robotic system to the rigid grounding member in the mouth of the patient, thereby establishing an origin for the mouth of the patient; developing a plan for automatically moving two or more of a plurality of surgical tools relative to the established origin to create the socket in the jawbone of the patient; attaching a first one of the plurality of surgical tools

to a working arm of the robotic system; executing a first portion of the developed plan by automatically moving the first one of the plurality of surgical tools via the working arm of the robotic system, thereby starting to create the socket in the jawbone of the patient according to the developed plan; receiving data from one or more sensors of the robotic system indicative of at least one of a torque or a force required to implement the first portion of the developed plan; modifying a second portion of the developed plan based on the received data; executing the modified second portion of the developed plan by automatically moving a second one of the plurality of surgical tools via the working arm of the robotic system, thereby completing the socket in the jawbone of the patient according to the modified plan.

Implementation 67. The method of implementation 66, wherein the first one of the plurality of surgical tools is a first surgical drill-bit tool having a first diameter and the second one of the plurality of surgical tools is a second surgical drill-bit tool having a second diameter that is larger than the first diameter.

Implementation 68. The method of implementation 66, wherein the first one of the plurality of surgical tools is a surgical drill-bit tool and the second one of the plurality of surgical tools is a surgical tapping tool.

Implementation 69. A method of using a robotic system comprising: developing a plan for automatically moving one or more of a plurality of surgical tools relative to an established origin of the robotic system to perform a surgical procedure in a mouth of a patient; attaching a first one of the plurality of surgical tools to a working arm of the robotic system; executing a first portion of the developed plan; during the execution of the first portion of the developed plan, receiving data from one or more sensors of the robotic system; and modifying a second portion of the developed plan based on the received data.

Implementation 70. The method of implementation 69, further comprising: attaching a rigid grounding member to a fixed position within the mouth of the patient; obtaining a pre-operative virtual model of the mouth of the patient with the rigid grounding member therein; and coupling a grounding arm of the robotic system to the rigid grounding member in the mouth of the patient, thereby establishing the origin for the mouth of the patient.

Implementation 71. The method of implementation 69, wherein the executing the first portion of the developed plan includes automatically moving the first one of the plurality of surgical tools via the working arm of the robotic system.

Implementation 72. The method of implementation 69, wherein the received data is indicative of at least one of a torque or a force imparted on the first one of the plurality of surgical tools required to implement the first portion of the developed plan.

Implementation 73. The method of implementation 69, further comprising executing the modified second portion of the developed plan.

Implementation 74. The method of implementation 73, wherein the executing the modified second portion of the developed plan includes automatically moving a second one of the plurality of surgical tools via the working arm of the robotic system.

Implementation 75. The method of implementation 74, wherein the first one of the plurality of surgical tools is a first surgical drill-bit tool having a first diameter and the second one of the plurality of surgical tools is a second surgical drill-bit tool having a second diameter that is larger than the first diameter.

41

Implementation 76. The method of implementation 69, wherein the modifying occurs in real-time during execution of the developed plan.

Implementation 77. The method of implementation 69, wherein the modifying includes changing a preplanned amount of torque to be used by the robotic system when executing the second portion of the developed plan.

Implementation 78. The method of implementation 69, wherein the modifying includes changing a preplanned rotational speed of one of the plurality of surgical tools to be used by the robotic system when executing the second portion of the developed plan.

Implementation 79. The method of implementation 69, wherein the modifying includes changing a preplanned amount of force to be used by the robotic system when executing the second portion of the developed plan.

Implementation 80. The method of implementation 69, wherein the modifying includes changing a preplanned number of the plurality of surgical tools to be used by the robotic system when executing the developed plan.

What is claimed is:

1. A method of creating a post-operative virtual model of at least a portion of a mouth of a patient, the mouth including a dental implant installed using a robotic system during a dental surgical procedure, the method comprising:

attaching a rigid grounding member to a fixed position within the mouth of the patient;

obtaining a pre-operative virtual model of the mouth of the patient with the rigid grounding member therein;

coupling a grounding arm of the robotic system to the rigid grounding member in the mouth of the patient, thereby establishing an origin for the mouth of the patient;

moving, as part of the dental surgical procedure, at least a portion of a working arm of the robotic system coupled to a dental-implant-driving tool to install the dental implant in the mouth of the patient;

monitoring, during the dental surgical procedure, a position of the grounding arm and the working arm to generate positional data related to the location of the dental-implant-driving tool relative to the established origin; and

creating, without scanning, a post-operative virtual model of the at least a portion of the mouth of the patient based on the obtained pre-operative virtual model and the generated positional data, the post-operative virtual model including a virtual dental implant that corresponds to a location and orientation of the dental implant in the mouth of the patient.

2. The method of claim 1, wherein the creating the post-operative virtual model occurs without use of a scanning abutment coupled to the installed dental implant.

3. The robotic system of claim 1, wherein the creating the post-operative virtual model of the at least a portion of the mouth of the patient includes modifying the pre-operative virtual model of the mouth of the patient to include at least a portion of a virtual model of the dental implant installed in the mouth of the patient.

4. The method of claim 1, wherein the working arm is coupled to the grounding arm.

5. The method of claim 1, wherein the working arm and the grounding arm are both electronically coupled to one or more processors of the robotic system.

42

6. The method of claim 1, further comprising: prior to the moving, determining an invisible boundary wall to be established around a pre-determined location for the dental implant to be installed in the mouth of the patient; and

during the moving, automatically enforcing the determined invisible boundary wall by preventing the working arm of the robotic system to be moved in a manner that would cause the dental implant to be installed outside of the determined invisible boundary wall.

7. The method of claim 1, wherein the rigid grounding arm of the robotic system is coupled to the rigid grounding member after the pre-operative virtual model of the mouth of the patient is obtained.

8. The method of claim 1, wherein the rigid grounding member includes a body and a coupling post extending from the body.

9. The method of claim 8, wherein the coupling post includes a receiving bore having a first central axis, wherein the origin for the mouth of the patient is positioned along the first central axis.

10. The method of claim 9, wherein the origin for the mouth is a single origin.

11. The method of claim 9, wherein the grounding arm includes a grounding probe configured to couple to the rigid grounding member in a removable and repeatable fashion.

12. The method of claim 11, wherein the grounding probe includes a coupling end, the coupling end including a pair of biased locking bearings that are biased outward away from a second central axis of the coupling end of the grounding probe.

13. A method of creating a post-operative virtual model of at least a portion of a mouth of a patient, the mouth including a dental implant installed using a robotic system during a dental surgical procedure, the method comprising:

attaching a rigid grounding member to a fixed position within the mouth of the patient;

obtaining a pre-operative virtual model of the mouth of the patient with the rigid grounding member therein;

coupling, after the pre-operative virtual model of the mouth of the patient is obtained, a grounding arm of the robotic system to the rigid grounding member in the mouth of the patient, thereby establishing an origin for the mouth of the patient;

moving, as part of the dental surgical procedure, at least a portion of a working arm of the robotic system coupled to a dental-implant-driving tool to install the dental implant in the mouth of the patient;

monitoring, during the dental surgical procedure, a position of the grounding arm and the working arm to generate positional data related to the location of the dental-implant-driving tool relative to the established origin; and

creating, without scanning, the post-operative virtual model of the at least a portion of the mouth of the patient based on the obtained pre-operative virtual model and the generated positional data, the post-operative virtual model including a virtual dental implant that corresponds to a location and orientation of the dental implant in the mouth of the patient.

14. A method of creating a post-operative virtual model of at least a portion of a mouth of a patient, the mouth including a dental implant installed using a robotic system during a dental surgical procedure, the method comprising:

attaching a rigid grounding member to a fixed position within the mouth of the patient;

obtaining a pre-operative virtual model of the mouth of the patient with the rigid grounding member therein;

43

coupling a grounding arm of the robotic system to the rigid grounding member in the mouth of the patient, thereby establishing an origin for the mouth of the patient;

determining an invisible boundary wall to be established 5
around a pre-determined location for the dental implant to be installed in the mouth of the patient;

moving, semi-manually and as part of the dental surgical procedure, at least a portion of a working arm of the robotic system coupled to a dental-implant-driving tool 10
to install the dental implant in the mouth of the patient;

during the moving, automatically enforcing the determined invisible boundary wall by providing an indication to a user that the working arm of the robotic system 15
is to be moved outside of the determined invisible boundary wall;

monitoring, during the dental surgical procedure, a position of the grounding arm and the working arm to generate positional data related to the location of the dental-implant-driving tool relative to the established origin; and

44

creating, without scanning, the post-operative virtual model of the at least a portion of the mouth of the patient based on the obtained pre-operative virtual model and the generated positional data, the post-operative virtual model including a virtual dental implant that corresponds to a location and orientation of the dental implant in the mouth of the patient.

15. The method of claim 14, wherein providing the indication to the user can include at least one of:

preventing the working arm of the robotic system to be moved outside the invisible boundary wall; and
providing tactile feedback to the user indicating that the working arm is to be moved outside the invisible boundary wall.

16. The method of claim 14, further including:
displaying to the user a virtual invisible boundary wall relative to the pre-operative virtual model, the virtual invisible boundary wall corresponding to the invisible boundary wall.

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